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Novel Impregnation System for Filament Winding

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Problem Description

The motivation of the project is the findings in the project work and previous work done at NTNU within impregnation systems for filament winding, and microscopy analysis.

The scope of the project is to design and test an impregnation system for the filament winding machine in the MTP Polymer Lab. The composite tubes wound with the new impregnation system will be compared with the current impregnation system.

Microscopy of the composite materials will be conducted and an evaluation of microscopy as a tool for quantitative quality control of composite materials will be carried out. In addition mechanical testing will be carried out.

The design of the impregnation system is limited to one prototype that will address the issues with greatest influence on the winding session and quality of the composite.

Abstract

A new enclosed impregnation system for the filament winding machine at NTNU has been designed and manufactured. The impregnation system concist of three main parts, the impregnation unit, resin reservoir and fixtures. The impregnation unit has three main parts, two aluminum parts that greates a sinusoidal shape, and a disposable PTFE tube. The fibers are only in contact with the PTFE tube and the resin. Winding with the new system was easy and did not lead to any issues. The composite quality was evaluated by mechanical testing and microscopy. Two types of composite tubes were wound with the system and with the resin bath system as a reference. The tubes were wound with 4 and 24 layers. The 4 layer tubes were tested in split-disk tensile tests. Results from the split-disk tensile test show that the apparent tensile strength of composite material, with an average of 1860.9 MPa, from the new impregnation system is comparable to the reference material, 1754.5 MPa. The 24 layer tubes were tested in short-beam shear conditions. The composite made with the new impregnation system had an average short-beam strength of 37.5 MPa, and the reference strength was 36.5 MPa. Taken into account the standard deviation of the tests there are grounds for stating that the new impregnation system makes composite material with short-term mechanical properties equal to the reference system.

Microscopy and image analysis was conducted on material made by the new system and the reference system. The image analysis software CellProfiler was used to make programs to identify fiber volume fraction and void content of the composites. Image analysis show that the 4 layer tube made with the new system has a lower fiber volume fraction than the reference tube, and lower void content. This indicates that the composite made with the new system has a high resin volume fraction. Analysis of the 24 layer tubes and 4 layer tubes made at different winding speeds indicate that the new impregnation system is capable of manufacturing composites with an average fiber volume fraction of 60.4 %.

The conclusion of the project is that the new impregnation system makes composite materials with short-term mechanical properties comparable to the reference system. The project did not identify anything that should discourage further developement of the impregnation system.

Sammendrag

Et nytt lukket impregneringssystem til filamentviklemaskinen til NTNU har blitt designet og produsert. Impregneringssytemet består at tre hoveddeler, impregneringsenheten, resin reservoir og festeanordninger. Impregneringsenheten har tre hoveddeler, to aluminimumsdeler som danner et sinusformet spor og en engangs PTFE slange. Fibrene er bare i kontakt med PTFE slangen og resinen. Vikling med det nye systemet var enkelt og det oppsto ingen problemer under viklingen. Kvaliteten på komposittmaterialet laget med det nye impregnerigssystemet ble gjort ved mikroskopi og mekanisk testing. Det ble viklet to typer kompositt rør med det nye impregneringssystemet og med resin bad systemet som et referanse system. Rørene som ble viklet besto av 4 og 24 lag med karbonfiber. Rørene med 4 lag ble testet i split-disk tensile test. Resultatene fra denne testen viser at den tilsynelatende strekkstyrken til komposittmaterialet fra det nye systemet, med et gjennomsnitt på 1860.9 MPa, er sammenlignbart med referanse materialet som hadde en tilsynelatende strekkstyrke på 1754.5 MPa. Rørene me 24 lag be testet i tre-punkts

bøying. Kompositten fra det nye systemet hadde gjennomsnittlig short-beam strength på 37.5 MPa, og referanse materialet hadde gjennomsnittlig styrke på 36.5 MPa. Tatt i betrakting statistikken i prøveseriene og standard deviasjoner så danner testene grunnlag til å si at det nye impregneringssystemet lager komposittmaterial med tilsvarende korttids mekaniske egenskaper som referanse systemet.

Det ble gjennomført mikroskopi og bildeanalyse på material laget bed både det nye systemet og referansesystemet. Bildeanalysen ble gjennomført ved hjelp av programvaren CellProfiler. CellProfiler ble brukt til å identifisere fibervolumfraksjon of void innholdet til komposittene. Bildeanalyse av 4-lagsrøret laget med det nye systemet viser at røret har lavere fibervolumfraksjon og høyere void-innhold enn referanserøret. Dette indikerer at rører har høyere innhold av resin. Analyse av 24 og 4-lagsrørene produsert ved forskjellige viklehastigheter indikerer at det nye systemet har kapasitet til å produsere komposittmaterial med en gjennomsnittlig fibervolumfraksjon på 60%.

Konksusjonen i prosjektet er at det nye impreneringssystemet produserer komposittmaterial med korttids mekaniske egenskaper på linje med referansesystemet. Det ble ikke identifisert noen faktorer som tilsier at videre utvikling av konseptet bør frarådes.

Acknowledgements

I would like to thank all the people at NTNU that has helped me with so many things during this project work. Erik Sæter who always lends a helping hand in the workshop and provides ideas to solve the issue at hand, and in cooperation with Eivind Hugaas teaching me how to operate the filament winding machine. Abedin Gagani has been a great help with the microscopy and sample preparation. Carl-Magnus Midtbø who's quick on his feet and setup the test machines whenever needed. Børge Holen, Roar Munkebye and Emil Valaker for making the test fixture in the lab, and helping out with solving practical issues along the course of the project. Most of all I would like to thank Kaspar Lasn, my supervisor, for his time and dedication to the project. Thank you all!

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1.1 Problem Description

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1.2 Motivation

NTNU's Polymer lab has a filament winding machine that is used for the manufacturing of tubes and pressure vessels for teaching and various research projects. The Filament Winding Machine(FWM), employs two rollers, a wheel and a resin bath for the impregnation of the filament tows.

An issue with this method of impregnation is that it requires extensive cleaning of the parts after the winding session is finished, which increases the cost and time per winding session. A secondary problem is related to the open air nature of the setup as there will be some spillage on the floor and on the impregnation unit itself. This has motivated NTNU to look into existing impregnation technologies and the possibility of adapting them for the winding machine in the polymer lab.

1.3 Framework

The framework for this project is two previous projects conducted at NTNU on the same topic. The first project was an internship project that looked into various methods of fiber impregnation and, based on an evaluation of these methods, built a prototype impregnation unit. The second project was the pre-project for this master's thesis. This project continues the work from the pre-project. The scope of the project is to develop a functioning proof-of-concept prototype of an enclosed impregnation system. This prototype shall be low-tech and not rely on automation or pumps. An important aspect of the project is to find,develop and apply evaluation methods for evaluating composite quality.

1.4 Previous work

Over the years of filament winding there have been many attempts to find different impregnation systems. Some of these systems have yielded successful results, while others have not. A common feature of many of the patented systems is that they are complex and require vacuum pumps, resin supply pumps or ultrasonic vibration. Both pumps and ultrasonic vibrators are considered outside of the scope for this project, due to cost and complexity.

During the spring and early summer of 2017 an internship project at NTNU started working on finding alternatives to the impregnation system. One student focused on building a prototype for fibre impregnation and testing that [1] while the other student focused on image analysis of the manufactured composites [2]. The prototype from the internship is a source of inspiration for this project.

1.5 Goals

The current impregnation system is fully functional and there is therefore not a need to replace it, but it would be preferable to have a new system that is easy to set up and clean. The fact that there is a working impregnation system implies that a new alternative system can not be expensive or complex. The project and impregnation system is therefore limited to an inexpensive proof of concept solution.

2 Literature

2.1 Filament winding

2.1.1 Application

Wet filament winding is a widely used technique for making tubes and pressure vessels. The winding setup typically consist of three main parts, the tension system where the dry fiber tows are placed, the impregnation system and the mandrel, see Fig 1.

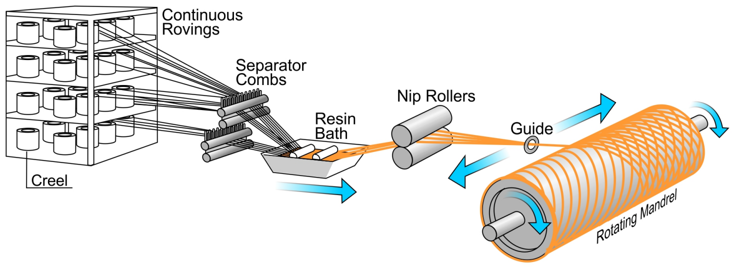


Figure 1: Typical winding setup. Creels placed in tensioning system, resin bath impregnation and mandrel [3]

The dry fibers go through the impregnation system and are wound on the mandrel following a predefined pattern. These predefined patterns vary depending on the desired function and critical loads of the component, but all patterns are variations of the three main winding patters: hoop (circumferential), helical and polar. Polar winding is similar to helical winding, the differences are that the angles are greater and the mandrel has two axis of rotation, see fig 2.

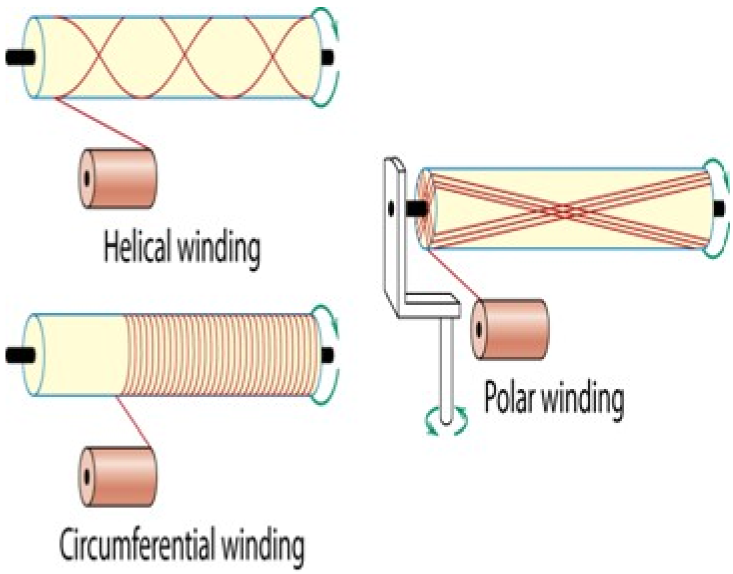


Figure 2: Hoop, helical and polar winding [4]

There are many advantages with using wet filament winding rather than other production methods such as cost, material properties, control over the process and the option to freely combine polymers and fibers. Although there are many advantages there are also disadvantages, and most of these disadvantages are linked to the setup, waste and spillage during the winding session.

2.1.2 Techniques

In a collaboration project between Institut für Verbundwerkstoffe GmcH and Montanuniversität Leoben the "Siphon impregnation" was developed[5]. The Siphon impregnation forces the polymer to impregnate the fiber rovings in a sinusodial cavity. The shape of this cavity develop three impregnation zones as the wetted rovings are pulled through, see Fig 3 and Fig 4.

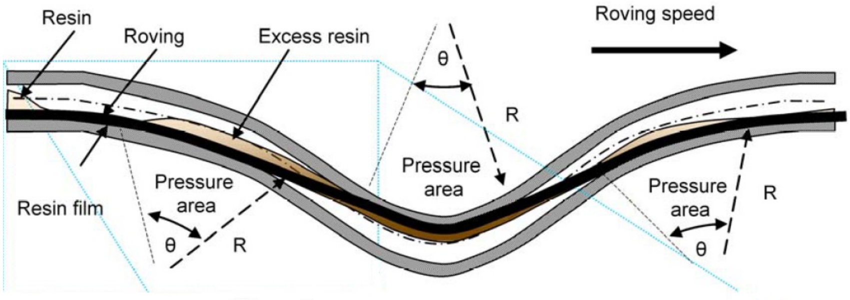


Figure 3: Impregnation zones marked as pressure area [5]

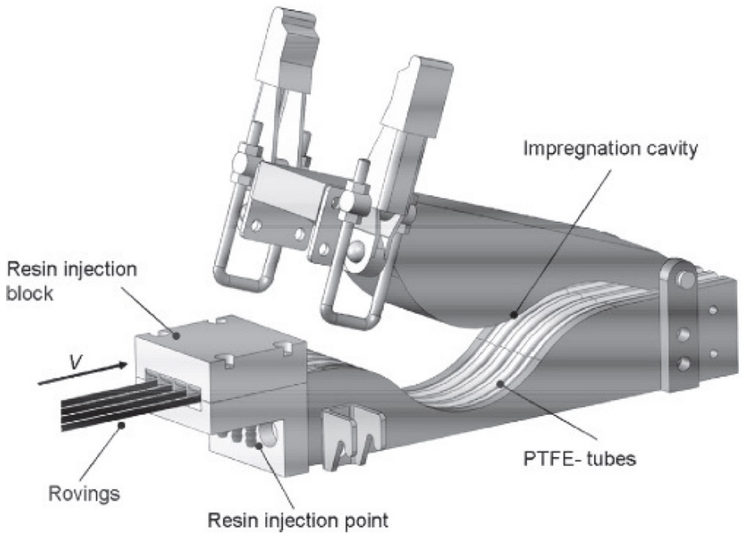


Figure 4: Siphon Impregnation setup[6]

The figure above shows the setup of the Siphon impregnation system. The setup consists of two metal parts that are clamped together over PTFE-tubes. This clamping assures that the PTFE tubes follow the sinusodial shape of the siphon while it also forces the tubes into an oval shape. Due to the oval shape of the tubes there is a flat region both at the top and bottom of the tube, by having these flat regions the carbon fiber tows remain flat through the impregnation, avoiding bundling of the fibers. If the fibers bundle together in the tubes the impregnation process is less effective and higher void contents would be expected. Another problem with bundled fibers is winding on the mandrel and height differences within a layer.

2.2 Composite Evaluation Techniques

Evaluation of composite quality is done using various test methods, both destructive and non-destructive. In this project three evaluation methods has been applied: tensile test, short-beam shear and microscopy with image analysis.

2.2.1 Microscopy and Image Analysis

Microscopy of composite materials is a powerful tool for identifying the structure of the composite material [7].Microscopy is used to visually examine the composite materials, and paired with image analysis it can identify fiber volume fractions, void content, resin pockets and other features of the material. Fiber volum fraction is a very important term in the manufacturing of composite materials. The fibers are the reinforcements in the composite and the strength of the composite is dependent on the amount of reinforcing fibers [8]. The fiber volume fraction is a percentage value of the volume of the material that is fibers. The average strenght of a composite can be calculated using this equation1

$$\sigma_c = V_f \sigma_f \ + (1 - V_f)\sigma_m \tag{1}$$

where V_f is the fiber volume fraction, σ_c is the average strength of the composite, σ_f is the average fiber strength and σ_m is the average matrix strength. In a composite the sum of the fiber volume fraction and the matrix volume fraction is equal to 1, and the matrix volume fraction can be found as one minus the fiber volume fraction.

Image analysis has wide range of applications, and the common denominator for these applications is that images contain sets of different features that should be identified. In this project image analysis is used to count fibers and to identify voids. The software used in the image analysis is CellProfiler 3.0.0. CellProfiler is an open source software designed for biologist with minimum programming skills. The software is based on modules that each do one or more changes to the image. The modules are set up in a Pipeline. The CellProfiler software can be downloaded for free at www.cellprofiler.org.

2.2.2 Short-Beam Strength

Three point bending was carried out according to ASTM D2344 [9]. This test identified the short-beam strength of fiber-reinforced composite materials. According to the standard the test does not directly relate to any one material property, but it can be used to compare composite materials in regard to manufacturing processes. The specimens have to fail by interlaminar shear for the test to be valid, and the interlaminar cracks should ideally be located in the same region of the specimens. If the specimens fail by different failure modes then the equations in D2344 can not be used to determine the short-beam strength of the composite.

The equations given in the standard relate to specimen geometry and calculation of short-beam strength [9]:

$$Specimen\ length = thickness\ x\ 6 \tag{2}$$

$$Specimen\ width, b = thickness\ x\ 2 \tag{3}$$

$$F^{sbs} = 0.75 \times \frac{P_m}{b \times h} \tag{4}$$

2.2.3 Split disk tensile test

Split disk tensile test is a tensile test where ring segments of a tube or pressure vessel can be tested and the apparent hoop tensile strength can be identified. The tests requires a specially designed test fixture. NTNU does not have this type of fixture, so one was designed for this project.

ASTM D2290 [10] defines the tests procedure of the split disk tensile test. The name of the standard is Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe. It is important to note the work Apparent. The test gives an apparent hoop tensile strength of the material, and not an actual hoop tensile strength. The reasoning for this distinction is that when a load is applied on the specimen during the test both a tensile stress and a bending moment is introduced in the specimen. Because the test does not apply a pure hoop tensile loading condition to the specimen it is not correct to state the results as hoop tensile strength.

3 New Impregnation System

3.1 Previous iteration

The impregnation system is a further development of a impregnation setup that has been developed and tested over the course of two previous projects. The first project identified different approaches for fiber impregnation such as ultra sonic vibrations, vacuum induced impregnation, resin bath impregnation, hydrostatic pressure and other methods of impregnation. Base on an evaluation of complexity, cost and results one of the systems were chosen to be the framework of that project. The selected impregnation system was the Siphon impregnation system developed by Institut für verbundwerkstoffe GmbH and Montanuniversitä Loeben [6]. In this first project a low tech prototype was made to identify the key aspects of the Siphon impregnation system, and to replicate the impregnation in a way that was as simple as possible. The second project was a second iteration of this impregnation system and the approach was to build an impregnation unit closer to the siphon impregnation system. Because it was a proof-of-concept prototype it was using plywood which could be easily modified and adjusted to account for unexpected issues that could arise during the project, see Fig 5.

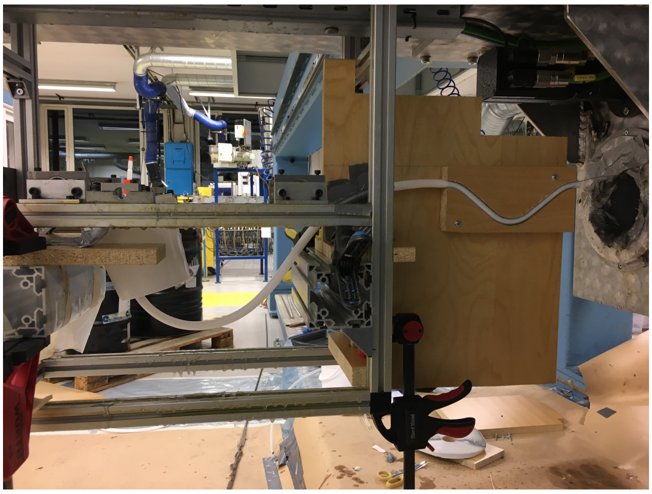


Figure 5: Mounted imregnation unit, pre-project

In this prototype the fibers entered the impregnation unit through the resin reservoir, the bucket in the left of Fig 5, and then entered the PTFE tube which was fixed in the milled sinusoidal groove in the plywood plate, Fig 6.

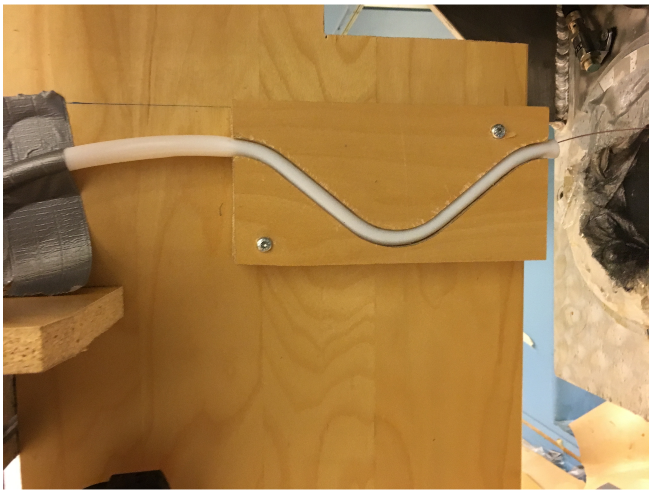


Figure 6: PTFE tube fixed in milled groove

The fibers were fully wettened during the winding sessions with this prototype, and as a impregnation concept it showed positive results.

This thesis project is another step in develop development of the results and concept of project two. Results from the pre-project showed that the concept was viable and could be further developed to become a well functioning impregnation system that produces high quality composite materials. The goal of this project is to develop a fully functional impregnation system built in long lasting materials.

3.2 Assembly, Design and Functionality

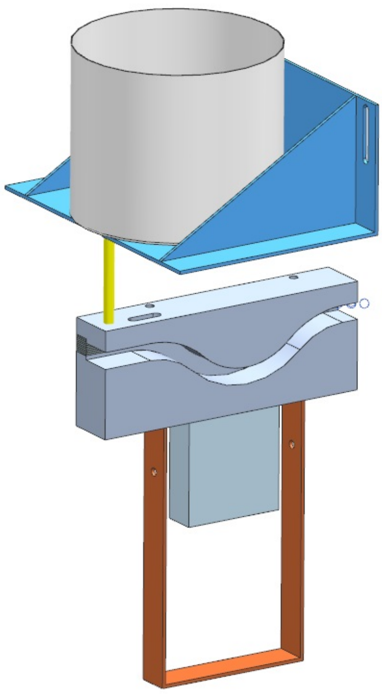


Figure 7: New impregnation system

The new impregnation system has three main parts, the resin reservoir, impregnation unit and fixture. The orange U and the blue bracket i Fig 7 are fixtures connecting the impregnation system to the frame of the filament winding machine. The bucket in the top of Fig 7 is the resin reservoir which is connected to the impregnation unit by a PE tube.

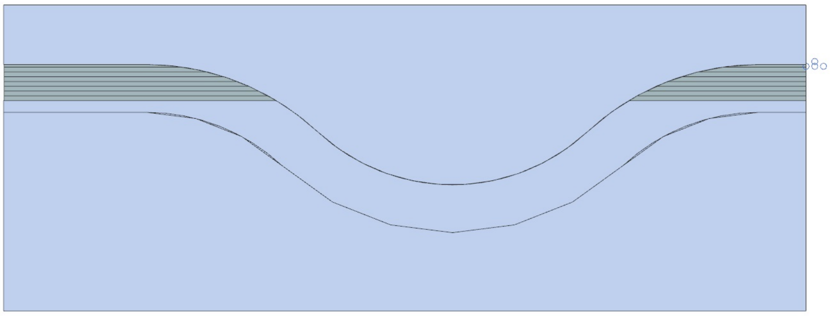


Figure 8: Impregnation unit

The impregnation unit is a three part unit, with the upper and lower parts creates a sinusoidal groove between them, the sinusoidal groove is designed according to relative dimensions given by the Siphon impregnation project, Fig 9. The lower and upper parts are connected with two bolts. Spacers are placed between the upper and lower part, this was designed to accommodate PTFE tubes of different dimensions. During the winding a disposable PTFE tube is fitted inside the groove and the bolts are tightened. Tightening the bolts compresses the PTFE tube and changes the shape of the PTFE tube from a cicle to an oval. Compressing the PTFE tube into an oval shape creates two plat regions in the tube, these regions are in contact with the aluminum parts of the impregnation unit. The flat regions alows the carbon fiber roving to pass through the impregnation unit while still remaining flat.

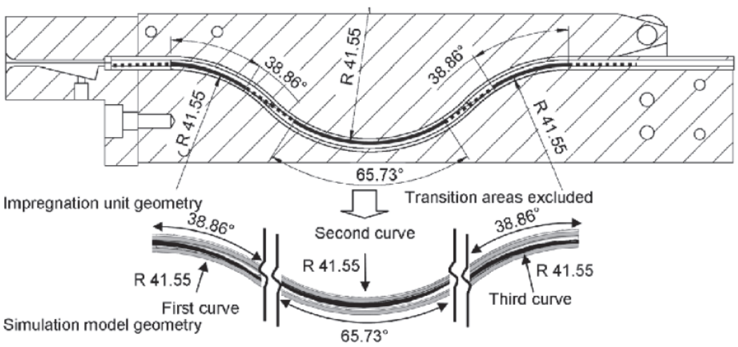


Figure 9: Relative dimensions,[6]

In the upper part of the impregnation unit there is a routed groove 10, This groove connects the resin delivery tube to the PTFE tube allowing resin to flow into the siphon. The resin entry point was made as a groove instead of a hole to allow for resin entry at different positions. The resin entry should be as close as possible to the start of the sinusoidal shape to maximize area wetted by resin and minimize the contact area between fibers and the dry PTFE tube. The trade off is that if the resin entry is to early in the flat regions of the PTFE tube in front of the sinusoidal shape it can lead to the resin

Figure 10: Resin entry groove to the left

flowing backwards and drip out of the PTFE tube. This is not an issue regarding the impregnation of the fibers because the fibers will be wetted either way, but it does impact spillage and clean up time. It is preferable if excess resin flows downwards inside the PTFE tube and collects at the bottom of the sinusoidal shape. If excess resin collects at the bottom of the sinusoidal shape it decreases spillage and acts as an impregnation buffer in that if the resin flow is to low the excess resin already collected in the bottom of the siphon will wett and impregnate the fibers while the operator increases the resin flow. Finding a good position for the resin entry will be done during the first finding session.

3.3 Realization

Resin delivery consists of three parts

- Resin reservoir
- Resin flow control
- Resin entry

The resin reservoir is a bucket that is located above the impregnation siphon. Placing the bucket above the siphon gives a hydrostatic pressure that ensures resin flow. The height of the bucket is adjustable, and can be lowered or lifted depending on the need for decreased or increased hydrostatic pressure. A flexible PE tube is connected to the resin reservoir by a 6 mm hole in the bottom of the bucket, the connection between the tube and bucket is sealed by sticky tape to prevent leakage. The flexible tube is pushed into the grove in the top of the siphon. Before connecting the PE tube to the siphon a resin flow control module is pushed onto the tube. This resin flow module is a solid piece of aluminum with a M12 bolt. The bolt adjusts the resin flow by reducing the open cross-sectional area of the PE tube. Fastening the bolt completely blocks the resin flow, and removing the bolt allows for the resin to flow freely through the tube. When the resin flow control module is connected the tube is pushed into the groove in the siphon. It is important that the M12 bolt is completely fastened when before adding resin to the resin reservoir.

The resin flow is controlled by the M12 bolt. A piece of tape was placed on one of the six corners on the head of the bolt when the bolt was completely tightened. During winding the resin flow will be adjusted as needed, and recording the position of the tape records the position of the M12 bolt, and the settings can be replicated in the next winding session.

The impregnation unit is connected to the winding machine by a U-shaped aluminum part that is fixed to the impregnation unit with two bolts. Tightening the bolts fixes the impregnation unit to the winding machine as the U-shaped aluminum part clamps onto a part of the frame on the winding machine. This method of fixing the impregnation unit to the winding machine allows for different positions of the impregnation unit. An aluminum block is placed between the frame and the impregnation unit. The function of this aluminum block is to position the impregnation unit at the correct height with respect to the frame. During the winding it is important that the fibers enter directly into the PTFE tube in the impregnation unit without coming in contact with any edges on the PTFE tube.

When the PTFE tube is fixed in the impregnation unit, the impregnation unit is fixed to the winding machine. The position of the impregnation unit is dependent on the shape of the PTFE tube. The PTFE tube extends beyond the impregnation unit on both the entrance and exit sides of the impregnation unit. These extended parts of PTFE tube have different shapes depending on the curvature of the tube and the length of the extensions. It is important that the carbon fibers do not come in contact with the ends of the PTFE tube, due to potential damage from scraping against the edges of the tube. When fixing the impregnation unit to the winding machine it is recommended that the carbon fiber is pulled through the impregnation unit, and the tension system is activated. Activating the tensioning system will straighten out the carbon fiber and show if and where the fibers come in contact with any edges. The impregnation unit is then oriented so there is no contact between fibers and any edges.

Setting up the system correctly is more time consuming than setting up the resin bath system. This is largely due to the fact that the resin bath system is easy to set up and the frame of the winding machine is designed to fit this system. Due to the variation in the shape of the extended parts of the PTFE tube the new impregnation system will potentially have a different position for each winding session and PTFE tube. The variation is only minor, but it does take some time to account for these small variations when setting up the system. When the system is correctly set up the variations should not impact the functionality of the impregnation.

4 Winding

The winding was split into two periodes of the project. The first winding period was carried out when the prototype was finished, and the the wound composite materials were tested. The second winding period was carried out after mechanical testing and microscopy of the composite material from the first winding period was finished.

Two new mandrels were made out of the standard 140 mm diameter PE-tubing material that NTNU uses as mandrels. The PE tube was cut to a length of 830 mm, and the ends was turned down to 136 mm to fit under the end domes that are used to keep the mandrel in place during the winding session. New mandrels were made instead of using the existing mandrels in the lab because repeated winding, and removal of the wound material can damage the tubes. The same end domes were used for all three winding sessions.

The fiber used for all tubes wound in this project is TORAYCA T700SC-12000 carbon fiber. This is a carbon fiber yarn with 12000 filaments, meaning that a single roving of this yarn consists of an average of 12000 carbon fibers. This carbon fiber has been widely used in NTNU's lab work, and it is the same fiber as the one used in the autumn project and the internship project. EPIKOTE RIMR 135 resin and EPIKOTE RIMH 137 hardener was the epoxy used in all the winding sessions. This is an epoxy that NTNU has extended experience in using as it is the standard epoxy in the NTNU polymere lab.

All settings and adjustments during the winding sessions were recorded to ensure that each winding session was carried out as similar as possible.

4.1 First winding

The first winding period in the project consists of three winding sessions. The first winding session was with the new impregnation system. The goal of the winding session was to identify basic winding parameters and especially to play around with the resin flow settings and get a feel of the effects of minor and major changes in the resin flow, and the delay between changing the setting and the effect of this change. The second winding session was also with the new system and the experience from the first winding session was incorporated from the start. This experience allowed the winding session to start with reasonable resin flow settings that ensured that the first layers of the composite would be fully wettened and impregnated. If the first layers are not properly impregnated due to resin flow issues the entire composite would have to be discarded and the a new winding session would be necessary. The third winding session was with the original resin bath impregnation setup. This is a known impregnation method and the composite from this session acts as a reference point with respect to the microscopy, three-point bending and split-disk tensile tests.

4.1.1 Winding parameters

One windin session manufactures one tube. Each tube has two segments, one 500 mm wide segment of 4 layers and one 200 segment of 24 layers. The winding program, made with the Winding Expert software installed on the Mikrosam winding machine, was set to 700 mm of 4 layers and 200 mm of 20 layers. The 200 mm of 20 layers was layed on top of the 700 mm 4 layer segment, resulting in a 200 mm wide 24 layer program.

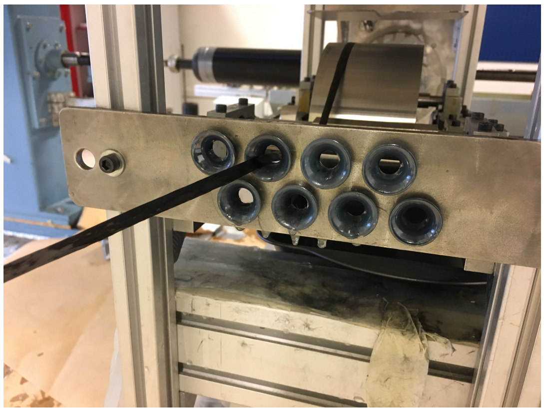
- Program settings

- Bandwidth 5 mm
- Speed 20 $\frac{m}{min}$
- pre-tension 40 N
- Mandrel dimensions
  * Diameter 140 mm
  * Length 800 mm

During the winding sessions the winding speed was set to 20% which should mean 20% of the preset speed in the winding program. In the winding manager, the software that control the winding machine, there is a setting to adjust the speed while winding. This setting is set as a percentage value. It was persumed that this percentage value corresponded to the predefined speed in the winding program.

The roving was placed in the fiber tensioning unit of the winding machine. Some of the ceramic fiber guides on the winding machine has been damaged by spilled epoxy and can not be used for winding, there are two fiber guides that can be used, and the one in the top left corner was used for winding with the new setup, see Fig 11a. Ideally the same fiber guide should have been used when winding with the original resin bath system, but this fiber guide palaces the fiber at the very edge of the big wheel, and the fiber slips off during the winding session. The fiber guide to the right of the one used for the new system was therefore chosen instead, see Fig11b. This is a difference in setup that should have been avoided, but it was only discovered after the winding with the new system had been completed.

(a) Entry point, new system



(b) Entry point, Resin bath

Figure 11: Ceramic Guides

4.1.2 Notes during winding

First winding session The goal of the first winding session was primarily to identify baseline settings for the resin flow bolt. The bolt was tightened fully before the winding started, and a piece of tape was placed on the head of the bolt. This piece of tape acts as a reference point when adjusting the resin flow. A second piece of tape was placed on the

PE resin delivery tube. This tape indicates the maximum depth of which the PE tube can be pressed down into the impregnation unit. If the PE tube is pushed further down it can come in contact with the carbon fibers, and that could lead to fiber damage.

Figure 12: Bolt, fully tightened

The winding started with the bolt opened $\frac{1}{2}$ revolution, but this did not deliver enough epoxy, and the fibers on the mandrel looked dry. The opening was increased to $\frac{2}{3}$ revolution. When any adjustments to the bolt is made the winding is stopped as a safety precaution. This allows for resin to flow into the PTFE tube and epoxy starts collecting in the tube. After making the adjustment the winding resumed. The $\frac{2}{3}$ provided enough resin for a short time before the fibers started to look dry. The winding was stopped and the bolt was adjusted to $\frac{5}{6}$ revolution opening. This was the setting for the remainder of the 4 layer segment of the tube. These adjustments were made based on visual observation of the wound material and the amount of excess resin on the mandrel, see Fig 13

Figure 13: First layer, first winding session

When winding of the 20 layer segment started the winding speed was increased from

20 % to 40 % speed to see if that had any influence on the impregnation. To account for this increased speed the opening of the bolt was increased to 1 $\frac{1}{6}$ revolutions. This was the setting for the entire 20 layer segment of the winding.

Second Winding Session The second winding session was with the new system and the goal was to apply the knowledge about the resin flow throughout the winding session. The 4 layer segment was wound with the bolt opened $\frac{5}{6}$ revolutions. This seemed impregnate the fibers without accumulating excessive resin amounts on the mandrel, see Fig 14

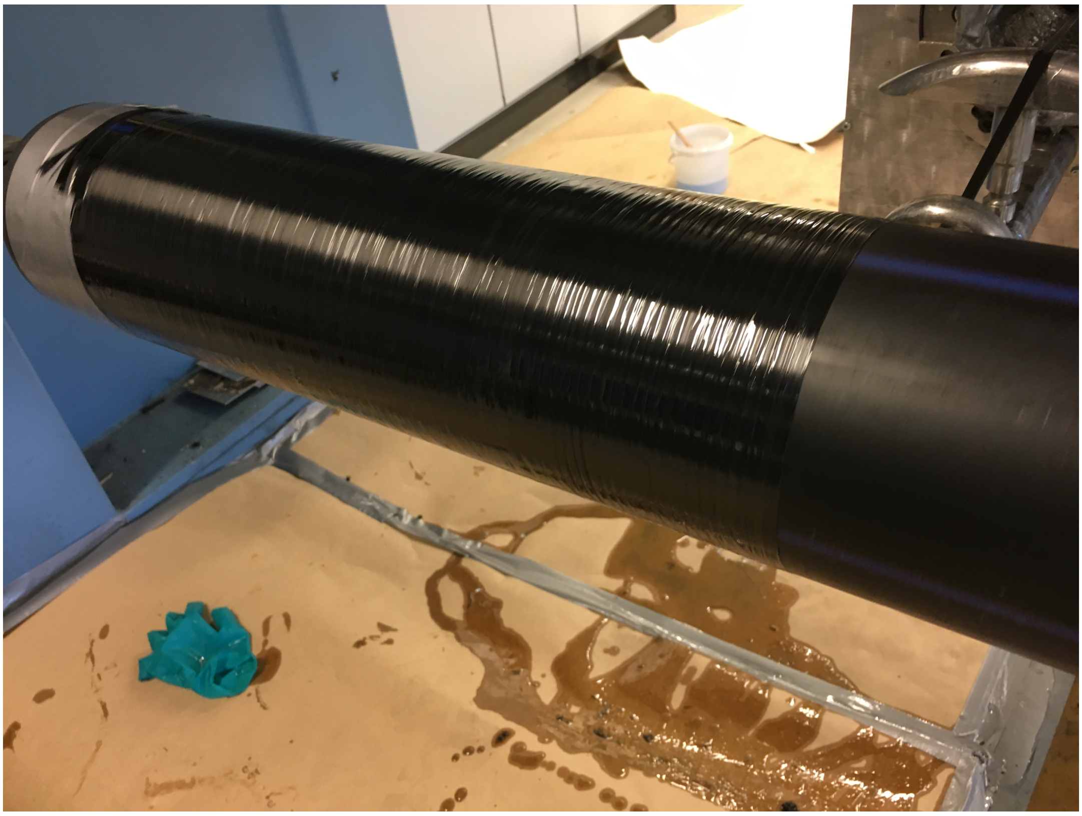


Figure 14: First layer, second winding session

The 20 layer segment was wound at 20% speed, with the bolt opened 1 revolution. No issues was encountered during the winding session.

Reference winding The third winding session was with the resin bath impregnation system. The material from this tube acts as a reference in the mechanical tests and microscopy. 100 mm of the 4 layer segment of this tube was fitted with optical fibers in between layer 2 and 3. Optical fibers were also fitted between layer 8 and 9 in the 20 layer segment, this corresponds to layers 12 and 13 respectively, in the 24 layer composite. The optical fibers were fitted because it is of interest to NTNU to identify if optical fibers influence the mechanical properties of composites. The effects of optical fibers is focused on in this project, but the results are included.

The optical fibers were spaced 5 mm apart, this corresponds to one carbon fiber roving bandwith between the optical fibers. This spacing is closer than optical fibers are normally placed, and it is done to amplify any effects that the optical fibers may have on the mechanical properties, and also to ensure that the test specimens will contain at least one optical fiber. Optical fibers are difficult to see while they are being placed on the mandrel. Pieces of paper was placed with 10 mm intervals on the area where the fibers were to be connected. The pieces of paper are reference points for placing the fiber, and the paper was removed after the fiber was in place, see Fig 15

Figure 15: Fixing optical fibers

4.2 Second Winding

The second winding period of the project was done after the mechanical tests and microscopy had been carried out on the composites from the first winding period. The goal of the winding

4.2.1 Winding parameters

The goal of the second winding session was to identify how the winding speed influence the quality of the composite material. All three tubes in the first session were wound at 20 % speed. It was persumed that setting the speed to 20% speed would mean that the speed was 20% of the 20 $\frac{mm}{min}$ that was the defined speed in the project for the winding program. This is not correct. The default speed of the winding machine is 50 $\frac{m}{min}$ which means a speed setting of 20 % means 20% of 50 $\frac{m}{min}$, not 20 % of 20 $\frac{m}{min}$. To evaluate the influence of winding speed on the composite quality two new tubes were wound at speed settings that differ greatly from the first winding session. One tube was wound at 5% speed and the other at 80% speed. The layup of the tubes were the same as with the original tube, with a region of 4 layers for Split Disk testing, and a region of 24 layers for Short-Beams Shear testing. Another goal of the session was to place optical fibers in parts of the 4 layer region to have more data to analyze the effect of optical fibers the composite qualtiy.

4.2.2 Notes during winding

5% speed Started the winding with the resin control bolt opened $\frac{2}{6}$ opened. This setting provided a resin flow greater than the amount that was carried away by the fibers. After winding about half of the first layer the resin control bolt tightened to $\frac{1}{6}$ opening. This setting provided a resin flow that maintained the amount of resin in the PTFE tube. This setting was used for both the 4 layer and 24 layer regions of the 5% tube, there was no visual indication that it needed to be changed. There was no visual indication of any fiber damage during the winding and there was no issues.

80% speed The 80% speed tube was wound on the same mandrel as the 5% tube and the winding started just as the 5% speed tube was finished. The resin was the same as for the 5% speed tube, which means that the resin was not new or fresh. This can have an influence on the results. Before starting the first region of the 80% tube the resin contol bolt was opened to $\frac{4}{6}$. The PTFE tube was filled with resin before the winding started. When the winding started it became apparent that the resin flow needed to increase greatly, and the resin contol bolt was opened to $\frac{9}{6}$. This increase was not enough. The resin flow was increased to $\frac{12}{6}$. The fibers were still too dry. Further opening of the resin control bolt did not seem to increase the volume flow notably and it still needed to be increased. Finally the resin control bolt was removed completely to allow the resin to flow freely through the delivery tube. This was the setting for the remainder of the 80% speed tube. Removing the bolt did not result in a great enough resin flow and the fibers looked dry, and almost no resin was removed when the operator tried to scrape of excess resin. It is likely that the PE-tube was deformed after winding the 5% and did therefore not return to its original shape when the resin control bolt was removed.

5 Mechanical Testing

5.1 Short-Beam strenght

Three point bending was carried out on ten specimens, five from the tube wound with the new impregnation system, and five manufactured with the original system. All tests were carried out according to ASTM D2344 [9]. As stated in Chapter 5 of the standard the results from a short-beam test are not generally possible to relate to any one material property, but the failures are normally dominated by resin and interlaminar properties [9]. Given that the specimens have the same failure mode it is possible to use the short-beam test to compare the quality of the composites.

5.1.1 Test set-up

A MTS 5kN tensile test machine was used for the testing. The three point bending fixtures consist of two parts; support rollers and the loading roller. The diameter of the loading roller is 6 mm, and the support rollers 4 mm. The supports were placed with a span-to-thickness ration of 4:1 of the average thickness of each test series.

The loading speed was set to 1 $\frac{mm}{min}$.

ASTM D2344 [9] defines the recomended specimen geometry if the thickness is equal or less than 6 mm. The average thickness of the composites made with both the new and the original impregnation system had average thicknesses greater than 6 mm. In the case of thicker specimens ASTM D2344 [9] reccomends these proportions:

$$Specimen\ length = thickness\ x\ 6 \tag{5}$$

$$Specimen\ width, b = thickness\ x\ 2 \tag{6}$$

Due to the 5 kN load capacity of the test machine the specimens were made with a specimen width less than 2 x thickness. This was based on the results in the autumn project where the failure loads were between 3 kN and 5.5 kN. The main reason for this big variation in failure loads were the differences in specimen geometry, which can be seen from the Short-Beams strengths that had less variation and varied from 28 MPa to 36 MPa. Based on this information and the assumption that the specimens would have similar Short-Beam strengths it was decided to reduce the width of the specimens to 12 mm, which is below the recommended 2 x thickness. These failure loads of these 12 mm specimens were assumed be in the region 3.5 kN to 4.5 kN, which is well within the capacity of the test machine. The standard also states that curved specimens, which is the case in this test, should not exceed an arc of 30 degrees. This was not measured, but the length of the specimens were, and the radius of curvature is known to be equal to the radius of the mandrel, and can therefore be calculated.

	New 5 %	80 %	New % trial	New 20%	Resin bath	Resin bath w/ optical fiber
t1 [mm]	6,49	6,55	6,65	6,52	6,92	6,96
t2 [mm]	6,47	6,52	6,66	6,51	6,91	6,97
t3 [mm]	6,48	6,54	6,66	6,50	6,92	6,95
t4 [mm]	6,50	6,54	6,68	6,50	6,92	6,96
t5 [mm]	6,50	6,56	6,69	6,51	6,92	6,96
w1 [mm]	11,88	11,83	11,84	11,92	11,61	11,07
w2 [mm]	11,96	11,83	11,86	11,94	11,68	11,18
w3 [mm]	11,95	11,81	11,83	11,95	11,67	11,20
w4 [mm]	11,94	11,78	11,84	11,98	11,68	11,21
w5 [mm]	11,87	11,72	11,83	11,97	11,68	11,17
L1 [mm]	40,42	41,35	44,31	44,14	45,01	43,57
L2 [mm]	44,36	45,43	40,58	40,43	40,86	39,49
weight [g]	5,06	5,15	5,14	5,00	5,23	4,81
Number of specimen	10	9	8	11	8	8

Table 1: Average specimen geometry

$$\bar{x} = \Big(\sum_{i-1}^{n} x_i\Big)/n \tag{7}$$

$$S_{n-1} = \sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\big(\bar{x}\big)^2\right)/\big(n-1\big)} \tag{8}$$

Where:
$\bar{x}$ = sample mean;
S_{n-1} = Sample standard deviation;
n = number of specimens;
x_i = measured property.

5.1.2 Results

A total of 54 specimens were tested. The average results are presented in the table below, detailed results and specimen geometry for each test run can be found in Appendix D. Where New refers to the new impregnation system, and the percentage is the winding speed setting.

Specimen	Average [MPa]	Standard Deviation	CV	Number of specimen
Resin Bath	36.5	1.2	3.5	8
Resin Bath, w/ optical fibers	37.2	1.5	4.0	8
New 5 %	37.0	2.1	5.7	10
New 20 % Trial	37.5	1.3	3.5	8
New 20 %	34.3	3.0	8.8	11
New 80 %	37.3	1.1	3.1	9

Table 2: Short-Beam Shear Results

5.1.3 Failure modes

Two dominant failure mechanisms were observed during the tests. The first test series failed by one single centered crack originating at the edge of the specimens. This is expected failure mechanism in a Short-Beam strength test [9]. The other observed failure mode was the dominant failure mode every other test series. In these specimens small interlaminar cracks formed in the composite between the loading nose and one of the support rollers. Continued loading lead to a saturation of these small interlaminar cracks through the thickness of the composite. After reaching saturation the cracks grow simultaneously towards the edge of the specimen. Figure, Fig 16 show a typical graph of a specimen failing by this failure mechanism.

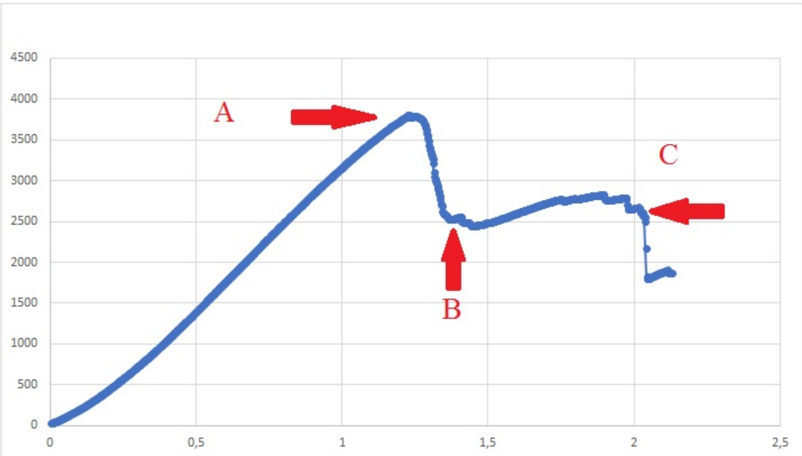


Figure 16: Representative failure development.

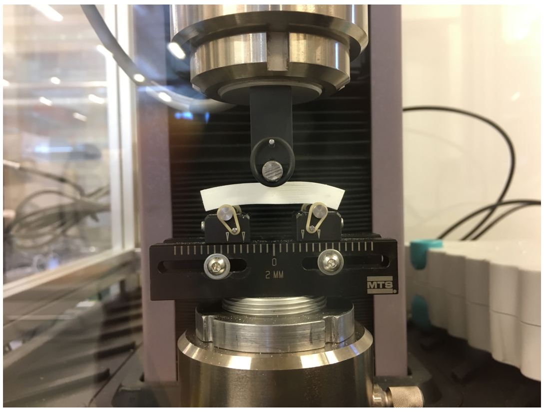


Figure 17: Point A, interlaminar cracks start to form

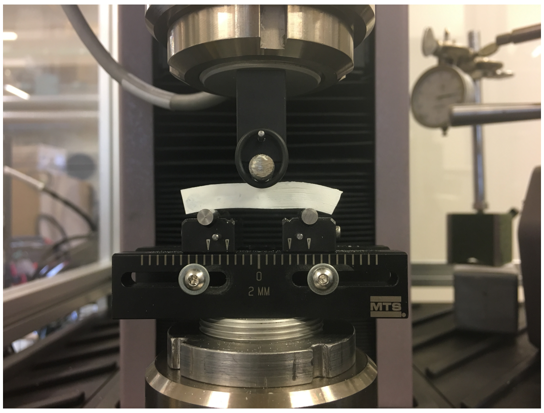


Figure 18: Point B: Cracks grow

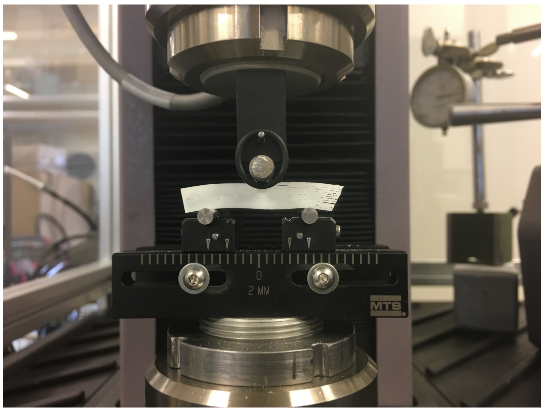


Figure 19: Point C: specimen is saturated with interlaminar cracks.

At point A the interlaminar cracks start to form, Fig 17, this happens at the peak load of the test. At point B, Fig 18, the stress starts to build up again and the crack continue to grow. At point C the cracks have reached the edge of the specimen, Fig 19

5.2 Apparent Hoop Tensile Strength

Apparent hoop tensile strength was tested by a Split-Disk tensile test. This is a test that is defined by the ASTM 2290 standard [10]. Split disk tensile test is carried out on notched circular ring segments. The split-disk method aims to reduce the influence of bending moment in the ring segment to achieve a setup that is as close to a simple tensile loading condition as possible. The results will be influenced by the bending moment, but as this test is carried out to compare two different impregnation systems the influence of the bending moment is not of any concern.

5.2.1 Equipment

Tensile test machine, with minimum capasity of 100 kN. Split disk

5.2.2 Specimen geometry and prepraration

Cicular segments of the tubes cut with a diamond saw, and placed in a jigg for grinding. The grinding ensured equal with of the widest regions of the specimens, and ensured controlled placement of the notches. The dimensions stated in ASTM D2290 are reccomendations for minimum dimensions, and it is up to the judgement of the designer to choose the final dimensions of the specimens. Average dimensions for each test series can be found in table 3 and the radius of the notch was 16 mm.

The jigg for grinding the specimens was made out of the same type of PE-tube that was used as the mandrell during the winding. After making about half of the specimens the grinding had removed too much of the PE material, and the jigg was discared. another jigg was manufactured to the same dimensions as the first jigg. The fact that the jigg loses material during grinding was expected, but the effect of it is that there are variations within the dimensions of the specimens. These are the average dimensions for each of the test series:

	5 %	5% F	80 %	20% trial	New 20%	resin bath	resin bath w/optical fibers
t1	1,13	1,11	1,11	1,23	1,16	1,17	1,20
t2	1,13	1,13	1,13	1,25	1,20	1,19	1,19
t3	1,15	1,12	1,14	1,23	1,17	1,17	1,22
t4	1,14	1,13	1,12	1,23	1,19	1,20	1,21
Wt1	23,80	23,81	23,72	24,10	23,77	24,90	24,72
wt2	14,93	14,61	14,14	15,20	13,64	15,74	15,04
wt3	24,09	23,89	23,74	24,39	23,86	24,81	24,64
w1	23,64	24,05	23,55	24,26	23,85	24,88	24,60
w2	14,73	14,90	14,35	15,56	13,63	15,59	14,75
w3	24,25	23,95	23,63	24,43	23,40	24,98	24,66
B2	23,39	23,28	22,99	23,96	23,26	24,40	18,16
B4	23,35	23,51	23,05	24,06	23,24	24,26	18,09
N	4	3	6	9	8	9	4

Table 3: Average specimen geometry, Split disk

5.2.3 Results

Specimen	Average [MPa]	Standard Deviation	CV	Number of specimen
Resin Bath	1754.5	145.4	8.3	9
Resin Bath, w/ Optical Fibers	1702.9	119.3	7.0	4
New 5 %	1788.5	183.5	10.3	4
New 5 % w/ Optical Fibers	1767.7	347.9	19.7	2
New 20 % Trial	1779.1	116.8	6.6	9
New 20 %	1860.8	75.4	4.1	8
New 80 %	1944.1	113.5	5.8	6

Table 4: Split-Disk Results

Where New refers to the new impregnation system, and the percentage is the winding speed setting.

6 Microscopy and Image Analysis

Microscopy was carried out to identify visual differences in the composite tubes and to use image analysis to identify Fiber Volume Fraction and Void content. Two specimens were made for each tube. The specimens were cut transverse to the fibers and along the fibers and embedded so they could be grinded and polished. Grinding and polishing was done in steps: FEPA 80 , 220, 500, 1200, 2000, 4000 then polished with 3 μm diamond paste. Each specimen was grinded a minimum of 3 minutes with each grinding step. The pictures were taken using Alicona con-focal microscope.

Images were captured at different 5, 10, 20 and 100 magnification. Images captured at x5 magnification are used to visually examine the composites. Visually inspecting the images will highlight differences between the composites that are not found in the image analysis. The image analysis focus on identifying fibers volume fractions and voids.

CellProfiler, and open source image analysis tool, was chosen for the image analysis. This is a module based image analysis tool where the user defines the workflow, so called pipelines, of the image analysis. Each step of the pipeline does one single change to the picture. This method of performing image analysis requires little to no programming skills, it is easy to operate once the pipeline has been constructed. and it requires little adjustments between pictures. In the summer of 2017 a internship student at NTNU conducted a project to develop different pipelines using CellProfiler, these pipelines and the findings in the project has been the starting point in developing the pipelines presented in this project.

6.1 Fiber Volume Fraction

Fiber volume fraction gives a clear indication of the strength of a composite material. The fibers are the load carrying components in the composites, while the resin bonds with the fibers making it into one composite material rather than thousands of independent fibers. Computing the fiber area fraction in a 2D image correlates to finding the fiber volume fraction of the composite. Fiber volume fraction is a three dimensional property, but if the two dimensional fiber area fraction is calculated from a picture taken completely transverse to the fiber direction, it should be equal to the fiber volume fraction. This is because the fibers are continuous and when the picture is taken completely transverse to the fiber direction the fiber direction is straight out of the plane of the picture. In that case the fiber volume fraction is found by multiplying the fiber area fraction by a factor of 1 dimensional unit.

6.1.1 Pipeline

The pipeline for image analysis is designed for analysing images at x100 magnification.

1. Crop The crop module removes the edges of the imported image. This is necessary to remove the image stamp the microscope software prints in the top left corner of the image. The crop module can also be used to adjust the image to exclude unwanted features such as the edge of the specimen.

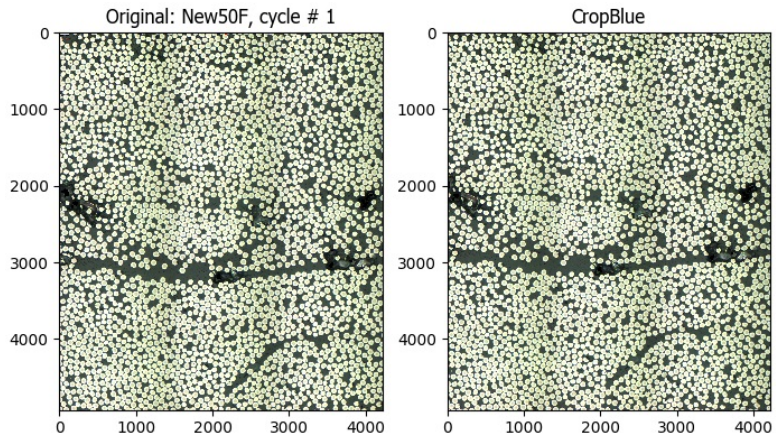


Figure 20: Crop, before and after

Color to Gray Images captured with the Alicona Con-Focal microscope are in color, even if they look as if they are black and white. This module takes the colored image and changes it to greyscale.

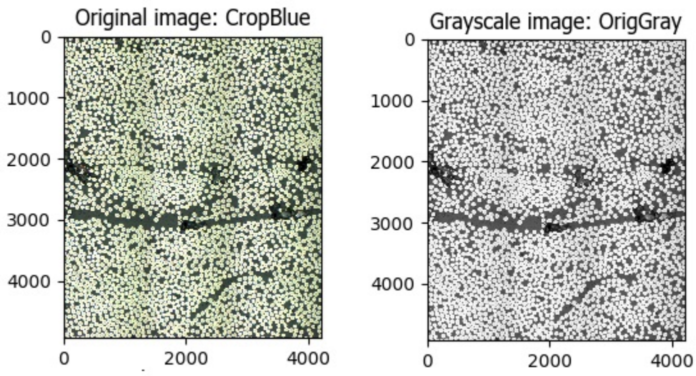


Figure 21: Color to grey

Rescale Intensity The rescale intensity module takes the greyscale image from the previous step and reassigns intensity values. Intensity values range from 0 to 1, where 0 is completely black and 1 is pure white. Rescaling the image using the setting "Strech each image to use the full intensity range" rescales the intensity of the image using the entire intensity range on each picture. This makes it easier to distinguish between features in the image in the following steps.

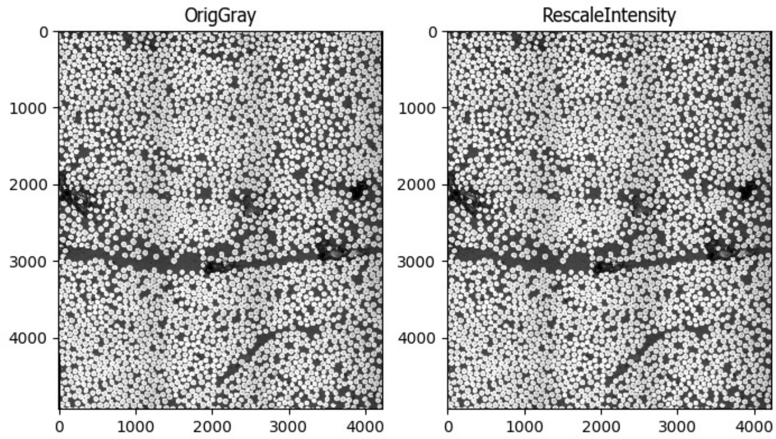


Figure 22: Rescale intensity

Correct Illumination Calculate This module calculates an illumination pattern in the image. The pattern can be applied to the image, resulting in a diluted image. Dilating the image means that the illuminated, white, objects blend and becomes more uniform. THe dilation is dependent on an appriximate object diameter and a dilation radius, these values were set to 80 and 2 in the analysis.

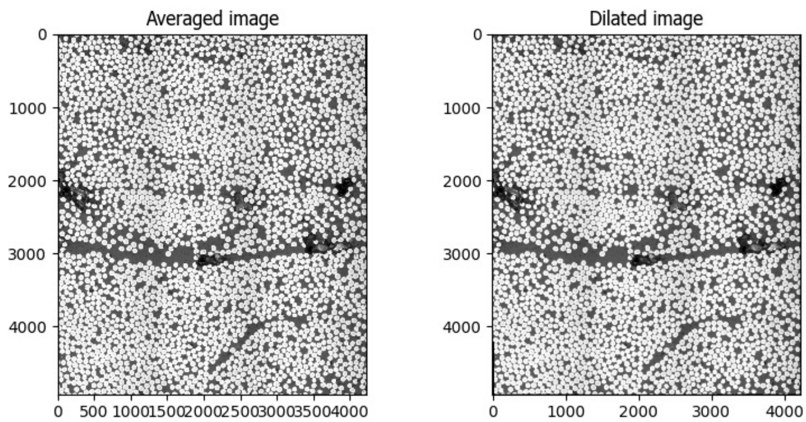
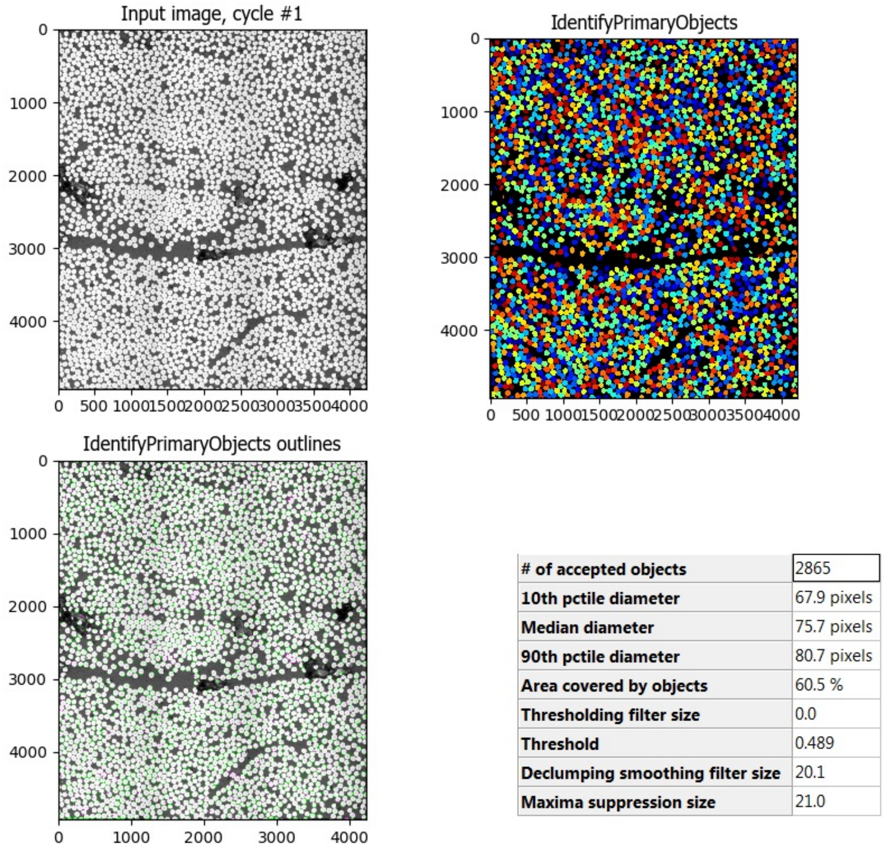


Figure 23: Correct Illumination apply, Dilated

Identify Primary Objects In this module the counting of the fibers start. There are two approaches to fiber counting, one is to define an approximate object size and shape and record the number of fibers. The second approach is the one used in this project, this approach counts the number of pixels that are within the object size range. The typical object diameter was set from 30 to 90 pixels, objects outside of this range will be discarded. This range was found to give results that correspond well with visual observations. The figure below, Fig 24, show the output of the identify primary objects module. In the top left corner the input image is printed, in the bottom lefte corner the identified objects are outlined. Green outline indicates that the object is accepted and within the diameter range, purple outline indicates that the outlined area is discarded as a object. In the top right corner the objects are colored. It is important to look closely at the input image and the colored image see if there are any discrepancies. In the bottom right corner is a table. This table show the number of accepted objects, and a percentage value of area covered by objects. This percentage value is the fiber volume fraction.



# of accepted objects	2865
10th pctile diameter	67.9 pixels
Median diameter	75.7 pixels
90th pctile diameter	80.7 pixels
Area covered by objects	60.5 %
Thresholding filter size	0.0
Threshold	0.489
Declumping smoothing filter size	20.1
Maxima suppression size	21.0

Figure 24: Identify objects

6.2 Voids

Voids in composite materials represent discontinuities within the material. Voids are closed pockets of air that do not contain fibers or resin material. These voids reduce the quality of the material, increase the volume of the material and decrease the short-beam strength of the material. Void can also act as internal local stress concentrations. In the microscopy images presented here voids are identified as black or dark regions within the image. Large grey areas are not voids, but resin pockets. Resin pockets are areas where an excessive amount of resin has been applied to the composite.

6.2.1 Pipeline

The pipeline is similar to the Fiber volume fraction pipeline, and the goal i to identify a set of object and find the area covered by these objects. The first three steps of the pipeline are the same as in the fiber volume fraction pipeline and are not repeated here.

Image Math After rescaling the colors of the image is inverted using the Image Math module and the invert setting. The inversion changes black areas from black to white, and white areas become black. Inverting the image makes it easier to visually check if the objects identified in the later modules are correct, see Fig 25.

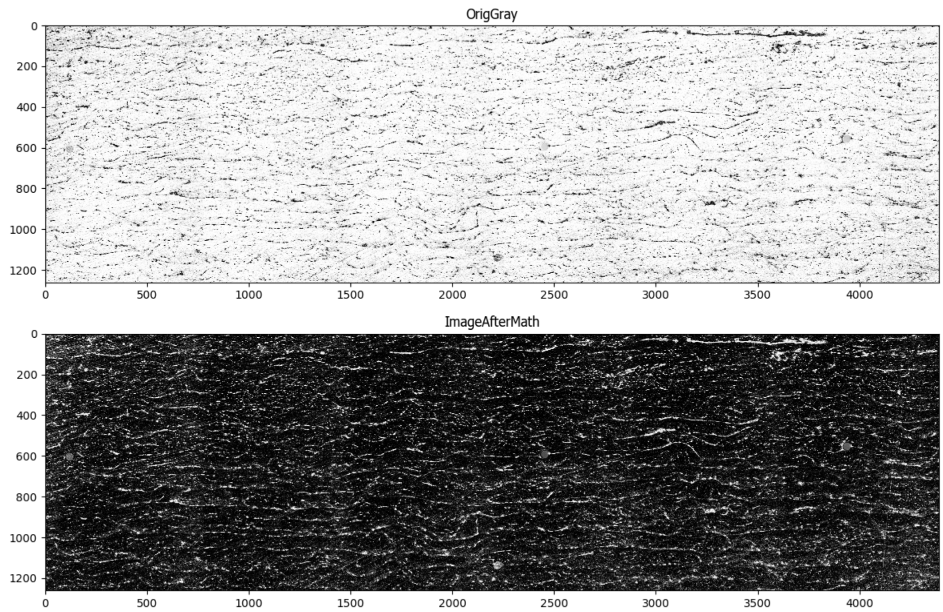


Figure 25: Image math, invert

Threshold The threshold module rescales the intensity of the image. A threshold value is set every pixel with intensity higher than that value is set to maximum intensity, 1.0. This enhances the contrast of the image and the voids become highly visible as white specks in the image.

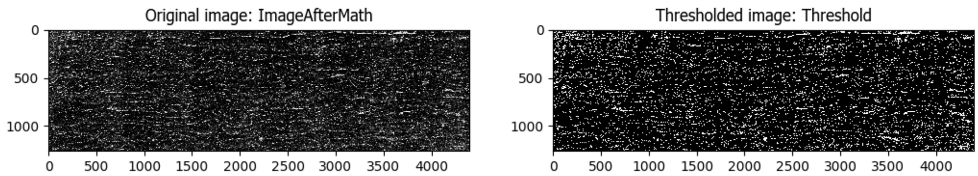


Figure 26: Threshold

Identify Primary Objects Identifying voids is different than identifying fibers. Voids do not have defined geometry or size. Therefore the typical object diameter has to be set to a large range to include both the small voids and the bigger voids. The range was set from 2 to 1000 pixels. This identified all voids that are visible in the images. If the composite contains large voids it is important to inspect that all the big voids are within the object diameter range and that they are included in the analysis.

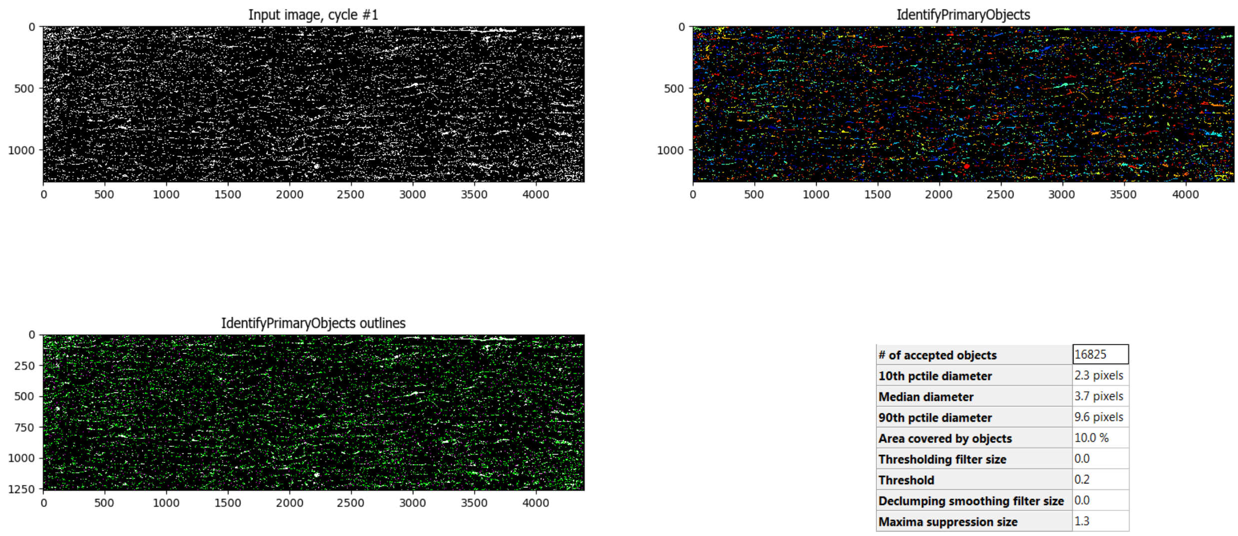


Figure 27: Identify primary objects, void

6.3 Results

Fiber volume fractions for the four layer segments are printed in Table 5.

image	Resin bath	New 80%	New 5%	New 20%	New 20%
1	51,2 %	58,1 %	60,5 %	48,9 %	41,9 %
2	55,6 %	58,9 %	56,0 %	42,0 %	42,6 %
3	59,0 %	52,4 %	56,5 %	39,7 %	53,3 %
4	51,6 %	56,7 %	58,4 %	44,4 %	52,9 %
5	48,7 %	45,9 %	57,0 %		
Average	53,2 %	56,5 %	57,8 %	43,7 %	49,5 %

Table 5: Fiber volume fractions, 4 layer segment

Fiber volume fraction for the 24 layer segments are printed in table 6

image	New 5%	New 80%	New 20%	New 20% trial	Resin bath
1	57,3 %	61,2 %	60,0 %	60,0 %	53,5 %
2	61,2 %	61,1 %			
3	61,4 %	60,2 %			
4	61,7 %	55,6 %			
Average	60,4 %	59,5 %	60,0 %	60,0 %	53,5 %

Table 6: Fiber volume fractions, 24 layer segment

Void content for both the 4 and the 24 layer segments are printed in table 7

Composite	4 layer	24 layer
New 5%	6,4 %	9,1 %
New 80%	10,4 %	8,2 %
New 20%	7,7 %	8,0 %
New 20% trial	6,3 %	7,3%
Resin Bath	9,6 %	9,9 %
Resin bath w/ optical fibers	10,0 %	-

Table 7: Void content

7 Discussion

This chapter will discuss the results of the concept development, use of the impregnation system and test results.

7.1 Concept

7.1.1 Setup

Setting up the system is easy, but it is more time consuming than setting up the resin bath impregnation system. The main reason for this is that the resin bath is quick and easy to set up and the winding machine is designed for this impregnation system. The most time consuming part of setting up the new impregnation system is fitting the PTFE tube as this needs to be done two times. The first time is to identify where on the PTFE tube the hole for the resin delivery tube needs to be cut. When that is identified the PTFE tube must be taken out of the impregnation unit to cut the hole properly. The hole can be cut while the PTFE tube is fixed in the impregnation unit, but this will lead to an uneven hole and sharp pieces of PTFE that, if not removed, can damage the fibers if they come in contact during the winding session. Fixing the PTFE tube in the impregnation unit the second time is easier because the PTFE tube still retains the sinusoidal shape of the impregnation unit.

7.1.2 Winding

When everything is set up winding with the new system proved to be very easy. The bolt controlled resin flow works well and changes in the resin flow are immediate. The fibers only came in contact with the PTFE part of the setup, and there was no visible frictional damage from any edges, faults of discontinuities in the system. Visual inspection of the PTFE-tube showed some black discoloration in the tube. These black regions were found in the parts of the siphon that has the highest friction, and in one place where the PTFE-tube had was bent in a way that produced a smooth internal edge.

Winding speed is controlled by setting a percentage value in the winding commander software that control the winding machine. It was presumed that this percentage value corresponded to the preset speed of the winding program, but this might not be the case. In the monitor of the winding machine there is a sensor that indicates the speed of the winding. During the 20% speed winding the monitor indicated a speed of 10 $\frac{m}{min}$, while the preset speed of the program was 20 $\frac{m}{min}$ which would mean that 20% speed should be 4 $\frac{m}{min}$. When winding the 5% speed it indicated 2.5 $\frac{m}{min}$, and the 80% speed was indicated as 40 $\frac{m}{min}$. If the monitor indicates the real winding speeds, then the preset winding speed is 50$\frac{m}{min}$, and not the 20$\frac{m}{min}$ that was defined in the program. This potential difference in winding speed does not have a major influence on the work done in the project. The winding speed had two applications in the project, the first application was that it ensured that the three first tubes were wound using the same winding parameters. The second application was testing if changing the speed influenced the mechanical properties of the composites. This was tested by winding tubes at 5% and 80% speeds. If the preset 100 % speed is 20$\frac{m}{min}$ or 50$\frac{m}{min}$ does not change the relation between the 5% 20% and 80%İt would be beneficial to know how the winding speed is defined, and this is something that should be included in the further work on the winding machine.

7.1.3 Disassembly and clean up

When the winding is finished the only parts that need cleaning and dissasembly are the two parts of the wining eye and the PTFE-tube. Removing the PTFE-tube is easy, it only requires that the two bolts connecting the impregnation unit are loosened one or two turns, and then the tube can be pulled out of the siphon.

The resin flow control bolt is fully tightened, ensuring that there will be no further resin flow. The remaining excess resin can cure in the bucket and be discarded when fully cured.

No issues regarding disassembly and clean up were found during the winding session of the project. There are fewer parts that need cleaning compared to the resin bath system, and the clean up process requires less time and acetone than the resin bath system.

7.2 Test results

The mechanical tests and image analysis has been used as a tool to evaluate the quality of the composite made by the new enclosed impregnation system. The purpose of the tests is to identify if there are any changes in mechanical properties or in the composition of the composite.

7.2.1 Short-Beam strength

Short-Beam shear tests on the composites show that the average values and coefficient of variation are comparable.

An important part of the Short-Beam shear test is to identify where in the composite the failures occur. Carbon fiber composites are black, and identifying small cracks are difficult. All specimens were painted white to ease the identification of the crack formation during and after the test. A short-beam shear test is valid if the crack occurs in the center of the composite and not at the. The specimens in every test series, apart from the first test series, all failed in the way that is explained in the results chapter. This type of failure sequence is not normaly observed during short-beam shear tests. One possible explanation for the observance of this failure sequence is that the specimens were painted white. The cracks that formed between the loading nose and the support rollers were very thing, and probably not be visible if the specimens had been black. Even though the specimens failed in an unusual way, the results from the tests give reasonable short-beam strengths. The highest average short-beam strength, 37.5 MPa, was for the composite made with the new system during the trial winding session. The lowest average short-beam strength was also for a composite made with the new system at 20% speed. The differences in the strength values are minor and the results are comparable. This is an indication that the new system does not negatively influence the interlaminar properties of the composite materials.

7.2.2 Apprarent hoop tensile strength

Results from the split disk tensile test show that the composites made by the new enclosed impregnation have apparent hoop tensile strength equal to the composites made by the resin bath impregnation system. The number of specimens varied between each test series, which influence the coefficient of variation within the results.

The fact that the failure stresses are comparable indicate that the new system does not increase damage to the fibers during winding compared to the resin bath. It is important to note that this does not mean that the impregnation system does not damage the fibers. It only indicates that the new system does not damage the fibers more than the resin bath system.

As in all mechanical testing sample preparation is important to the outcome. The specimens were cut with a diamond saw and then grinded. The grinding process also grinded the material PE material of the jigg. This way of preparing the samples leaves room for differences between the specimen geometry. Each specimen was measured, and the apparent tensile strength is calculated based on the geometry of each individual specimen.

Apparent hoop tensile strength was carried out with the new split disk tensile test fixtures that was made for this project. The split disk fixture was designed to fit speciemen that are withing the minimum requirements of the ASTM D2290 standard [10] and bigger. The fact that this is a new test fixture means that there is no prior experience on the use of this exact test setup.

7.3 Image analysis

The backbone of a good image analysis is the sample preparation. All specimens in this project work have been grinded and polished with the same equipment and settings, but there are still variations within the quality of this sample preparation. When the images perfectly grinded and polished there should be no visible scratches on the surface of the specimen. That was not the case for all the specimens in this project.

The aim of the microscopy was to capture representative images that covered the entire surface of the specimen a x5 magnification, a major portion of the surface at x10 magnification, image fields covering representative and important areas at x 20 magnification and minimum 4 images at x100 at random locations on the specimen. Images at x100 magnification are used to identify fiber volume fraction. Using such a high magnification eases the process of correctly identifying fibers, but the trade off is that the images cover a small area of the composite. To account for this trade-off several images were captured, these images were taken at different locations on the specimen.

7.3.1 Fiber Volume Fraction

As stated in the previous subsection there are several issues regarding image analysis that can greatly influence the results of the analysis. The main issue concerning fiber area fraction is to get images that represent the composite in an objective and reasonable way. The images have to be high resolution so the transition from fiber to matrix material is well identified. This requirement of high resolution mean that one single image covers less area of the composite. Image analysis on the four layer segments of the composite tubes indicate that widing with the new system at 20% speed makes a composite with an average fiber volume fraction of 43.7%, this is notably lower than the average fiber volume fraction of the original system of 53%. Winding with the new system at 5% speed and 80% speed gives the highest fiber volume fractions, 57.8% and 56.5% respectively. This means that according to the results of the image analysis the new impregnation system is capable of manufacturing composites fiber volume fractions equal to the resin bath impregnation system, but it is not a guarantee that it will be the case. Image analysis was conducted on 5 images taken at random locations on for the new system and orignal system. These random locations may not be representative of the composite as a whole.

7.3.2 Void content

The results form the void content image analysis show that the new system makes composites comparable to the reference system. Void content image analysis was done on images taken at x5 magnification. At this magnification sample preparation can greatly influence the outcome of the analysis. If the analyzed surface is not polished perfectly, the remaining scratches from grinding will create dark lines in the image. These dark lines can be identified as voids in the image analysis. Void content analysis of the composite material show that the total void content of composites made with the new system are at the same level as the reference system. The void content analysis is based on one specimen from each winding session. Several specimens should be prepared and tested to increase the validity of the results. Specimen preparation and microscopy is time consuming, and that is the reason why only one specimen was prepared for each winding condition.

8 Conclusions

A new enclosed impregnation system has been developed, built and applied to the filament winding machine at NTNU. Setting up the new system takes slightly longer than the resin bath, but decreases the clean-up time and number of parts that need cleaning. This reduction of parts and clean-up time reduces the amount of acetone consumed in each winding session which reduces the operators exposure to the chemical. Resin deliveryshows potential for better replicability compared to the resin bath system

Short-beam shear of the composite material did not significantly decrease compared with the original system. Composites wound at 5% speed and 80 % speed had similar Short-Beam strengths as the 20 % speed and the resin bath impregnation system.

Split-disk tensile tests show that the apparent tensile strength of the composite materials do not decrease compared with the resin bath. Results from split-disk tests show even higher average apparent tensile strength values compared to the original system. Apparent tensile strength is strongly dependent on fibre volume ratio. This indicates that the new system does not introduce new sources of fiber damage, and it may have even decreased the fiber damage compared to the resin bath impregnation system. Higher winding speeds did not decrease the apparent tensile strength, which indicate that fiber damage does not increase with increased speed

Microscopy of the composites made with the two impregnation systems show the composites are visually similar. Image analysis identified that fiber volume fractions and void content of the composites were similar, and there were no major differences.

Results from mechanical tests and microscopy indicate that the new impregnation system makes composite materials with short-term mechanical properties that are comparable with composites made with the resin bath impregnation system.

Based on microscopy analysis and mechanical testing it can be concluded that the impregnation system provides sufficient impregnation without introducing new sources of fiber damage greater than the fiber damage from using the resin bath. There are no indication of issues that should discourage the further development of the new enclosed impregnation system.

9 Further Work

9.1 Impregnation system

The impregnation module seems to work well and the fibers are properly impregnated. However there are several aspects of the impregnation step that could and should be improved:

- Resin reservoir
- Resin flow
- Assembly
- Clog guard

9.1.1 Resin reservoir

The resin reservoir works well, but with the current setup a hole has to be drilled into the bottom of the bucket. The tube is pushed through this tube and fixed in place with sticky tape. Although this proved to work well and there were no leaks it would be easier, and decrease the likelihood of leaks, if the bucket could be replaced by another reservoir that is manufactured to fit a tube of the correct diameter. This could be something like a funnel if the funnel has the right geometry and can store a reasonable amount of resin.

9.1.2 Resin flow control

Resin flow is controlled by a bolt that is tightened or loosened based on the need of increased of decreased resin flow. This method works fine for a prototype, but it would be much easier to have control over the resin amount if the resin flow was electronically regulated. This electronic control could be pumps that deliver a preset amount of resin according to the winding speed. If this is implemented it will increase the reproducibility of the system which increases the confidence in the manufactured composite material. It is necessary to that the final impregnation system at NTNU has a setup where the resin flow is dependent on the winding speed. Winding hoop layer with the existing manual bolt controlled system works fine, helical layers has not been wound with this system, but it is reasonable to assume that there could be issues with resin flow due to the large fluctuations of winding speed during helical winding. The wining speed is high when the wining eye moves from one dome to the next, but at the domes the effective speed of the fiber tow is virtually zero. This means that there are two likely scenarios that can occur with this resin flow controll method:

1. The tube fills with epoxy when wining over the domes
2. The fibers are dry when winding between the domes

Neither of these two outcomes will produce a high quality composite material.

9.1.3 Assembly

Some aspects of the assembly of the impregnation system can and should be improved. The improvements should seek to ensure that the system is assembled in exactly the same way each time. With the current assembly setup there is room for some variations in the orientation of the siphon. Variations are not inherently undesired, but the should be controlled.

9.1.4 Clogs

As identified in the pre-project for this master thesis clogs tend to form inside the PTFE tube. These clogs are caused by loose fibres originated from the fiber closet and fiber tensioning system. The loose fibers are not caused by the new impregnation system, but pulling the fibers through a close tube causes the loose fibers to accumulate during the winding session. A clog buildup has two outcomes, either minor clogs are accumulated inside the PTFE tube and the pulled out by the fibers resulting in a inconsistency in the composite material. Or the clog build-up remains inside the PTFE tube If the clog remains inside the PTFE tube it will continue to grow as winding proceeds, this will reduce the open cross-sectional area of the PTFE tube, decrease the impregnation regions in the siphon and increase friction on the fibers. The decreased cross-sectional area can lead to resin being scraped of the fibers, which give dry fibers in the composite. The decreased area of the impregnation regions can lead fibers that look well impregnated due to a coat of resin covering the fiber tow, while not being properly impregnated inside the fiber tow. Increased friction on the fibers by the clog can cause fiber damage that drastically reduce the quality of the composite.

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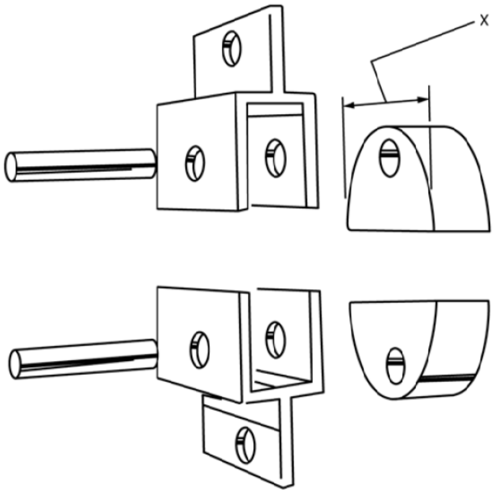
A Split disk tensile fixture

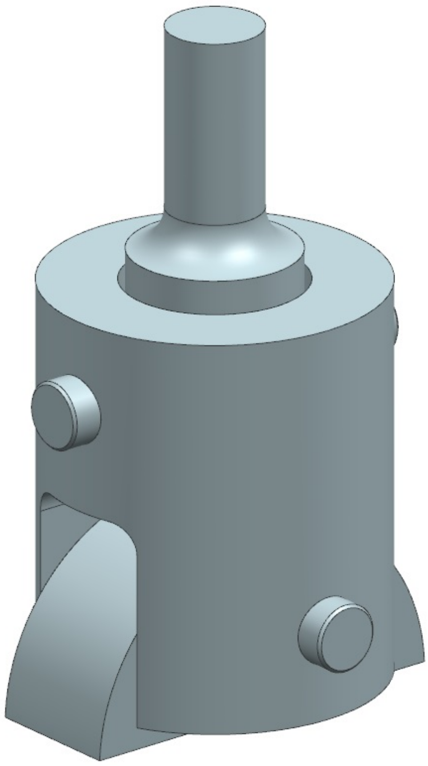
To evaluate if the new impregnation system introduces or increases the amount of damaged fibers split disk tests could conducted on composites made both with the new and the original system. There are standards regarding Split Disk testing, and the test fixture, Fig 28b, follows ASTM D2290 as closely as possible[10], some modifications were implemented following the suggestions given in SINTEF Material and Chemistry's study "Material characterisation and failure envelope evaluation of filament wound GFRP and CFRP composite tubes" [11].

[H]



[H]

(a) ASTM test setup [10]



(b) Test fixture designed for tensile experiments

Figure 28: Fixture for split disk tensile testing

The ASTM standard does not provide any dimensions for the test fixture, it only provides the minimum dimension of the test specimen. Also the fixture presented in the standard is not a self aligning fixture. It was decided to make the test fixture self aligning about two axis, this will reduce the influence of geometrical faults in the specimen and increase the likelyhood of uniform strain in the notched region of the specimen. The fixtures for the split disk tests were made with inspiration from SINTEF's fixtures and following Dr. Perillo's input.

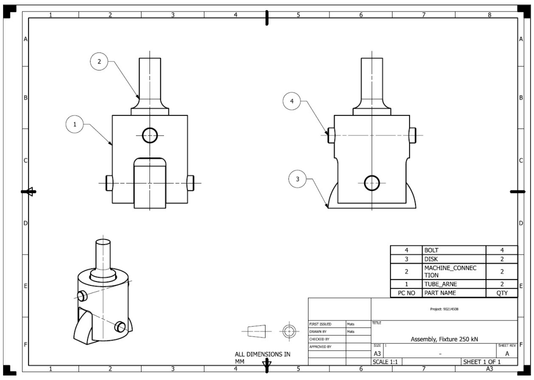
Specimens The specimens were disks cut from the 4 layer part of the tubes. The width of these disks varied between 25-30 mm. To be able to controll where on the disks the failure occurs four notches were grinding into the specimen as to pairs of notches. When the specimen is placed in the test fixtures the specimen is rotated so that the notches align with the gap in between the two half moon parts of the test fixture. In this region the disk will be subjected to tensile stress, with as little bending moment as possible.

Calculations and results The calculation is a simple stress calculation of force devided by area. Equation from ASTM D2290 28a:

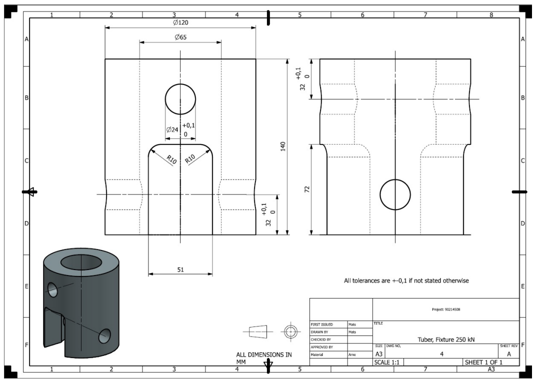
$$\sigma_a = \frac{P_b}{2 \times A_m} \tag{9}$$

Where σ_a is apparent yield or ultimate tensile stress, A_m is the by the notches. The area is multiplied by two because both the notched regions are testes.

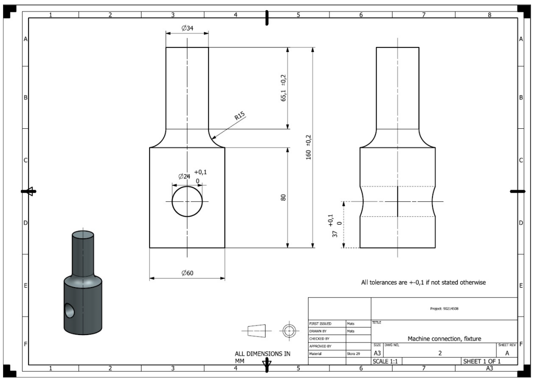
Drawings



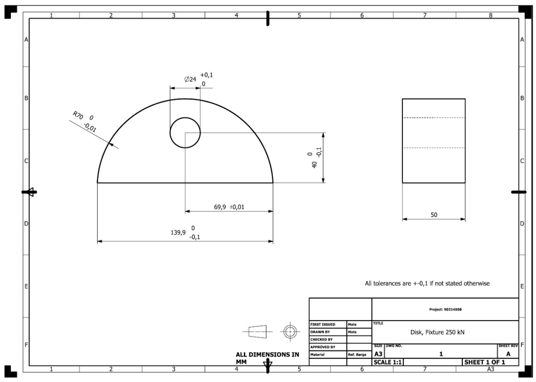
(a) Assembly



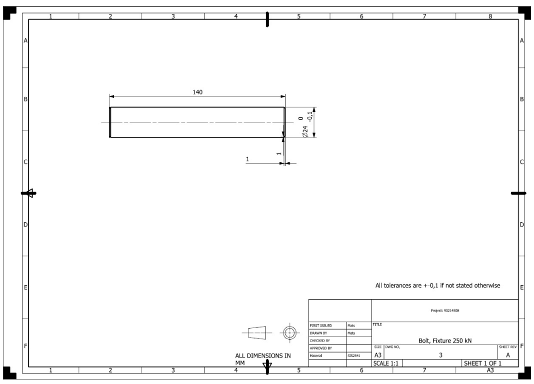
(b) Hole placement makes the fixture self aligning



(c) Connects to the test machine



(d) The only part in contact with the specimen



(e) Connection bolt

Figure 29: Drawings of fixture

B Risk assessment

Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

Safety and Quality Evaluation of Activities in the Laboratory and Workshop

NTNU

Perleporten

1 Identifikasjon - *Identification*	Dokumentnr. – *Document no.*:	
Kundenavn – *Customer name* NTNU Trondheim	Prosjektnavn – *Project name* Novel impregnation system for filament winding	Projektnr. – *Project no.*
The student will build, mount and test a new method for impregnation of fiber tows during filament winding. Tensile test and short beam shear tests in the Fatigue Lab at MTP. Microscopy of specimens.		Dato – *Date* 15.01.18 – 11.06.18

2 Projekt - *Team*			
Prosjektleder og organisasjon – *Project manager and organisation*	Kaspar Lasn, Nils Petter Vedvik, Mats Mulelid	Ansvarlig for instrumentering –*Responsible for instrumentation.*	N.A.
Leiestedsansvarlig – *Laboratory responsible*	Carl-Magnus Midtbø, Børge Holen, Gaute Stenerud	Operatør – *Operator*	Mats Mulelid
Auditør for sikkerhets og kvalitetsgjennomgang – *Auditer for safety check*	Carl-Magnus Midtbø, Børge Holen, Gaute Stenerud	Ansvarlig for styring av forsøk – *Responsible for running the experiment.*	Mats Mulelid, Kaspar Lasn
Ansvarlig for eksperimentelt faglig innhold – *Responsible for experimental and scientific content*	Mats Mulelid, Kaspar Lasn	Ansvarlig for logging av forsøksdata – *Responsible for logging and storing experimental data*	Mats Mulelid
Ansvarlig for dimensjonering av last og trykkpåkjente komponenter – *Reponsible for dimensioning load bearing and pressurized components*	Mats Mulelid	Ansvarlig for montering av testrigg – *Responsible for building the rig*	Mats Mulelid

3 Viktig!! – *Important!!*	J: Ja – *Yes* / N: Nei - *No*
Er arbeidsordren signert? – *Is the work order signed?*	N.A.
Har operatøren nødvendig kurs/trening i bruk av utstyret? - *Has the operator the required courses/training on the equipment?*	J
Har operatøren sikkerhetskurs? (påbudt) – *Has the operator followed the safety courses? (mandatory)*	J
Kan jobben gjøres alene? - *Can the work be done alone?*	J*
- Dersom ja, er det med visse forbehold (for eksempel, må bruke alarm, ha avtale med noen som kommer innom med jevne mellomrom eller lignende). Dette må vurderes i Seksjon 5. *If yes, the work may have to be done under special conditions (e. g. must use the alarm, have agreement with somebody coming back periodically or similar). This shall be evaluated in Section 5.*	

4.1 Sikkerhet – *Safety* (Testen medfører – *The test contains*)			J: Ja – *Yes* / N: Nei - *No*
Stor last – *Big loads*	J	Brannfare – *Danger of fire*	N
Tunge løft – *Heavy lifting*	N	Arbeid i høyden – *Working at heights*	N
Hengende last – *Hanging load*	N	Hydraulisk trykk – *Hydraulic pressure*	J
Gasstrykk – *Gas pressure*	N	Vanntrykk – *Water pressure*	N
Høy temperatur – *High temperature*	N	Lav temperatur – *Low temperature*	N
Deler i høy hastighet – *Parts at high velocity*	J	Farlige kjemikalier – *Dangerous chemicals*	J
Sprutakselerasjon ved brudd – *Sudden acceleration at fracture/failure*	J	Forspente komponenter – *Pre-tensioned components*	N
Farlig støv – *Dangerous dust*	J	Kraftig støy – *Severe noise*	J
Klemfare – *Danger of pinching*	J	Roterende deler – *Rotating parts*	J

4.2 Påkrevet verneustyr – *Required safety equipment*			J: Ja – *Yes* / N: Nei - *No*
Briller (påbudt) – *Glasses (mandatory)*	J	Vernesko – *Safety shoes*	N
Hjelm – *Helmet*	N	Hansker – *Gloves*	J

Skjerm – *Screen*	J	Visir – *Visir*	N
Hørselsvern – *Ear protection*	J	Løfteredskap – *Lifting equipment*	N
Yrkessele, fallsele, etc. – *Harness ropes, other measures to prevent falling down.*	N		

5.1 Beskrivelse av aktivitet – *Description of the activity (see Appendix)*

Vurdering skal være basert på en skriftlig prosedyre for bruk av maskinen. I enkelte tilfeller kan prosedyre bli beskrevet direkte i tabellen nedenfor.	*The evaluation shall be based on a written operating procedure for the machine. For simple cases the procedure can be directly described in the tables below.*

Nr.	Beskrivelse av aktivitet – *Description of activity*	Fare - *Danger*	Lov, forskrift o.l. – *Legal requirements*	Prosedyre nr. – *Procedure no.*	Sannsynlighet – *Probability*	Konsekvens –*Consequence*	Risiko – *Risk*
1	Cutting/sawing/sample preparation	Cutting fingers	NTNU HMS		2	B	B2
2		High noise	NTNU HMS		5	A	A5
3		Dust, breathing and in eyes	NTNU HMS		5	A	A5
4		Equipment damage	NTNU HMS		2	B	B2
5	Bending steel tube	Crush injury	NTNU HMS		2	C	C2
6	Mixing epoxy	Spillage on clothes and skin	NTNU HMS		4	A	A4
7		Breathing fumes	NTNU HMS		4	A	A4
8	Filament winding	Crush injury	NTNU HMS		1	D	D1
9		Spillage of epoxy	NTNU HMS		4	A	A4
10		Machine damage	NTNU HMS		2	A	A2
11		Breathing carbon fibers	NTNU HMS		2	B	B2
12		Getting caught by mandrel	NTNU HMS		2	C	C2
13	Tensile and SBS test	Machine damage	NTNU HMS		2	B	B2
14		Crush injury	NTNU HMS		3	C	C3
15		Hit by fragments	NTNU HMS		2	A	A2
16	Microscopy	Machine damage	NTNU HMS		2	C	C2
17	Assembly of prototype	Damage to the FWM	NTNU HMS		2	B	B2
18	Burn Off test	Burning hands/skin	NTNU HMS		3	C	C3

5.2 Korrigerende Tiltak – *Corrective Actions*

Nr.	Korrigerende tiltak – Corrective action	Sannsynlighet – *Probability*	Konsekvens – *Consequence*	Risiko – *Risk*	Utført dato – *Date of action*
1	Be carefull and alert. Place hands and fingers as far away from the saw blade as possible	2	B	B2	22.01.18
2	Hearing protection	1	A	A1	22.01.18
3	Wear mask and glasses, if appropriate	2	A	A2	22.01.18
4	Follow training and be carefull	2	B	B2	22.01.18
5	Ask for help and guidance, be carefull	1	B	B1	22.01.18

6	Wear lab coat and gloves, no exposed skin	1	A	A1	22.01.18
7	Use ventilated cabinet in the composite lab. Wear mask if appropriate	1	A	A1	22.01.18
8	Keep distance from the machine, place barriers. Light barriers active	1	B	B1	22.01.18
9	Wear lab coat and gloves, no exposed skin	2	A	A2	22.01.18
10	Follow manual. Operate at reasonable speeds	1	A	A1	22.01.18
11	Keep ventilation on at all times	1	A	A1	22.01.18
12	Keep away from fiber tows while winding is in progress. No long-sleeved clothes and cover long hairs.	1	B	B1	22.01.18
13	Activate load and position limits on the machine	2	B	B2	22.01.18
14	Activate load protect when placing samples	1	A	A1	22.01.18
15	Wear safety spectacles and use the protective screen	1	A	A1	22.01.18
16	Act according to training	1	A	A1	22.01.18
17	Do not mess with any of the important parts of the machine	1	B	B1	22.01.18
18	Wear protective gear	2	B	B2	22.01.18

Sikkerhets og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

NTNU
Perleporten

5.3 Feilkilder – *Reasons for mistakes/errors*

Sjekkliste: Er følgende feilkilder vurdert? – Check list: Is the following considered? J: Ja – *Yes* / N: Nei - *No*

Tap av strøm – *Loss of electricity*	Y	Overspenning – *Voltage surge*	N
Elektromagnetisk støy – *Electromagnetic noise*	N	Manglende aggregatkapasitet av hydraulikk – *Insufficient power of the machine*	N
Jordfeil – *Electrical earth failure*	N	Vannsprut – *Water jet*	N
Ustabilt trykk av hydraulikk/kraft – *Unstable pressure or hydraulic force*	Y	Tilfeldig avbrudd av hydraulikk/kraft – *Unintended interruption of power supply*	Y
Last-/ forskyvnings grenser etablert ? – *Are load and displacement limits established?*	Y	Lekkasjer (slanger/koblinger, etc.) – *Leakage of pipes, hoses, joints, etc.*	Y
Mulige påvirkninger fra andre aktiviteter – *Possible interference from other activities*	Y	Mulige påvirkninger på andre aktiviteter – *Possible interference towards other activities*	Y
Problemer med datalogging og lagring – *Troubles in loading and storage*	Y	Brann i laboratoriet – *Fire in the laboratory*	

6 Kalibreringsstatus for utstyr – *Calibration of equipment*

(ex: load cell, extensometer, pressure transducer, etc)

I.D.	Utstyr - *Equipment*	Gyldig til (dato) – *Valid until (date)*
1	Mechanical test machines	Laboratory calibration
2	Filament Winding Machine	N.A
3	Microscope	Laboratory calibration?
4	Scale in composite lab	N.A.
5	Saw	N.A.
6	Grinding and polishing equipment	N.A.

7 Sporbarhet – *Tracebility*

Eksisterer – Is there	J: Ja – *Yes* / N: Nei - *No*
Er alle prøvematerialene kjente og identifiserbare? – *Are all experimental materials known and traceable?*	Y
Eksisterer det en plan for markering av alle prøvene? – *Is there a plan for marking all specimens?*	Y
Er dataloggingsutstyret identifisert? – *Is the data aquisition equipment identified?*	Y
Er originaldata lagret uten modifikasjon? – *Are the original data stored safely without modification?*	Y
Eksisterer det en backup-prosedyre? – *Is there a back-up procedure for the data (hard disk crash)?*	Y
Eksisterer det en plan for lagring av prøvestykker etter testing? – *Is there a plan for storing samples after testing?*	Y
Eksisterer en plan for avhending av gamle prøvestykker? – *Is there a plan for disposing of old samples?*	Y

8 Kommentarer – *Comments*

There are four stages to the project:

1. Building a prototype. HMS and room training has been completed to gain access to the labs.
2. Winding test-tubes. This will be done following the procedures established by NTNU, and with support from experienced users of the machine.
3. Testing using the Instron 100kn machine or similar equipment. The operator has experience with this machine from his work in the Product and Material testing course. If any problems or questions arise the operator will contact the appropriate people.
4. Microscopy analysis.

* Section 3 Page 1: The work can be done alone as long as it is within the regulations and laws concerning laboratory work at NTNU, and as long as it does not pose any danger to the operator. If the work is in an area where people will pass by regularly, like the fatigue lab, it can be seen as working together with others. If the work is done in an area where people are not likely to pass by or see the operator, then the operator should contact the person responsible for that specific lab before starting the work.

9 Signaturer – *Signatures* *Godkjent (dato/sign) – Approved (date/signature)*		
Prosjektleder – *Project leader*	Verifikatør – *Verifier*	Godkjent – *Approved by*
Mats Mulelid	~~Kapitan~~ (K. LASN) 26.01.2018	Carl-Magnus Midtbø

Sikkerhets og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid	**NTNU** **Perleporten**

APPENDIX Bakgrunn - Background

Sannsynlighet vurderes etter følgende kriterier:

Probability shall be evaluated using the following criteria:

Svært liten Very unlikely **1**	**Liten** Unlikely **2**	**Middels** Probable **3**	**Stor** Very Probable **4**	**Svært stor** Nearly certain **5**
1 gang/50 år eller sjeldnere *– Once per 50 years or less*	1 gang/10 år eller sjeldnere *– Once per 10 years or less*	1 gang/år eller sjeldnere *– Once a year or less*	1 gang/måned eller sjeldnere *– Once a month or less*	Skjer ukentlig *– Once a week*

Konsekvens vurderes etter følgende kriterier:

Consequence shall be evaluated using the following criteria:

Gradering *– Grading*	**Menneske** *– Human*	**Ytre miljø, Vann, jord og luft** *– Environment*	**Øk/materiell** *– Financial/Material*	**Omdømme** *– Reputation*
E **Svært Alvorlig** ***– Very critical***	Død – Death	Svært langvarig og ikke reversibel skade *– Very prolonged, non-reversible damage*	Drifts- eller aktivitetsstans >1 år. *– Shutdown of work >1 year.*	Troverdighet og respekt betydelig og varig svekket *– Trustworthiness and respect are severely reduced for a long time.*
D **Alvorlig** ***– Critical***	Alvorlig personskade. Mulig uførhet. *– May produce fatality/ies*	Langvarig skade. Lang restitusjonstid *– Prolonged damage. Long recovery time.*	Driftsstans > ½ år Aktivitetsstans i opp til 1 år *– Shutdown of work 0,5-1 year.*	Troverdighet og respekt betydelig svekket *– Trustworthiness and respect are severely reduced.*
C **Moderat** ***– Dangerous***	Alvorlig personskade. *– Permanent injury, may produce serious health damage/sickness*	Mindre skade og lang restitusjonstid *– Minor damage. Long recovery time*	Drifts- eller aktivitetsstans < 1 mnd *– Shutdown of work < 1 month.*	Troverdighet og respekt svekket *– Troverdighet og respekt svekket.*
B **Liten** ***– Relatively safe***	Skade som krever medisinsk behandling *– Injury that requires medical treatment*	Mindre skade og kort restitusjonstid *– Minor damage. Short recovery time*	Drifts- eller aktivitetsstans < 1uke *– Shutdown of work < 1 week.*	Negativ påvirkning på troverdighet og respekt *– Negative influence on trustworthiness and respect.*
A **Siker** **- Safe**	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day	

Risikoverdi = Sannsynlighet X Konsekvenser

Beregn risikoverdi for menneske. IPM vurderer selv om de i tillegg beregner risikoverdi for ytre miljø, økonomie/ material og omdømme. I så fall beregnes disse hver for seg.

Risk = Probability X Consequence
Calculate risk level for humans. IPM shall evaluate itself if it shall calculate in addition risk for the environment, economic/material and reputation. If so, the risks shall be calculated separately.

Risikomatrisen
Risk Matrix

I risikomatrisen er ulike grader av risiko merket med rød, gul eller grønn:

Rød: Uakseptabel risiko. Tiltak skal gjennomføres for å redusere riskoen.

Gul: Vurderingsområde. Tiltak skal vurderes.

Grønn: Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

Når risikoverdien havner på rødt felt, skal altså enheten gjennomføre tiltak for å redusere risikoen. Etter at tiltak er iverksatt, skal dere foreta ny risikovurdering for å se om risikoen har sunket til akseptabelt nivå.

For å få oversikt over samlet risiko: Skriv risikoverdi og aktivitetens IDnr. i risikomatrise (docx) / risikomatrise (odt). Eksempel: Aktivitet med IDnr. 1 har fått risikoverdi 3D. I felt 3D i risikomatrisen skriver du IDnr. 1. Gjør likedan for alle aktiviteter som har fått en risikoverdi. En annen måte å skaffe oversikt på, er å fargelegge feltet med risikoverdien i skjemaet for risikovurdering. Dette tydeliggjør og gir samlet oversikt over riskoforholdene. Ledelse og brukere får slik et godt bilde av risikoforhold og hva som må prioriteres.

In the risk matrix different degrees of risk are marked with red, yellow or green;

Red: Unacceptable risk. Measures shall be taken to reduce the risk.

Yellow: Assessment Area . Measures to be considered.

Green: Acceptable risk. Measures can be evaluated based on other considerations.

When a risk value is red, the unit shall implement measures to reduce risk. After the action is taken, you will make a new risk assessment to see if the risk has decreased to acceptable levels.

To get an overview of the overall risk: Write the risk value and the task ID no . the risk matrix (docx) / risk matrix (odt) . Example : Activity with ID no . 1 has been risk value 3D. In the field of 3D risk matrix type ID no . 1 Do the same for all activities that have been a risk . Another way to get an overview is to color the field of risk value in the form of risk assessment . This clarifies and gives overview of the risk factors . Management and users get such a good picture of the risks and what needs to be prioritized.

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge		Beskrivelse
Rød		Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul		Vurderingsområde. Tiltak skal vurderes.
Grønn		Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

Til Kolonnen "Korrigerende Tiltak":

Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs sannsynlighetsreduserende tiltak foran skjerpende beredskap, dvs konsekvensreduserende tiltak.

For Column "Corrective Actions"

Corrections can influence both probability and consequence. Prioritize actions that can prevent an event from happening.

Oppfølging:

Tiltak fra risikovurderingen skal følges opp gjennom en handlingsplan med ansvarlige personer og tidsfrister.

Follow Up

Actions from the risk evaluation shall be followed through by an action plan with responsible persons and time limits.

Etterarbeid #

- Gå gjennom aktiviteten/prosessen på nytt.
- Foreta eventuell ny befaring av aktiviteten/prosessen for enten a) å få bekreftet at risikoverdiene er akseptable eller b) for å justere risikoverdiene.
- Gå gjennom, vurder og prioriter tiltak for å forebygge uønskede hendelser. Først skal dere prioritere tiltak som reduserer sannsynlighet for risiko. Dernest skal dere ta for dere tiltak som reduserer risiko for konsekvenser.
- Tiltakene skal føres inn i handlingsplanen. Skriv fristen for å gjennomføre tiltaket (dato, ikke tidsrom) og navn på den / de som har ansvar for tiltakene.
- Foreta helhetsvurdering for å avgjøre om det nå er akseptabel risiko.
- Ferdig risikovurdering danner grunnlag for å utarbeide lokale retningslinjer og HMS-dokumenter, opplæring og valg av sikkerhetsutstyr.
- Ferdig risikovurdering og eventuelle nye retningslinjer gjøres kjent/tilgjengelig for alle involverte.
- Sett eventuelt opp kostnadsoverslag over planlagte tiltak.